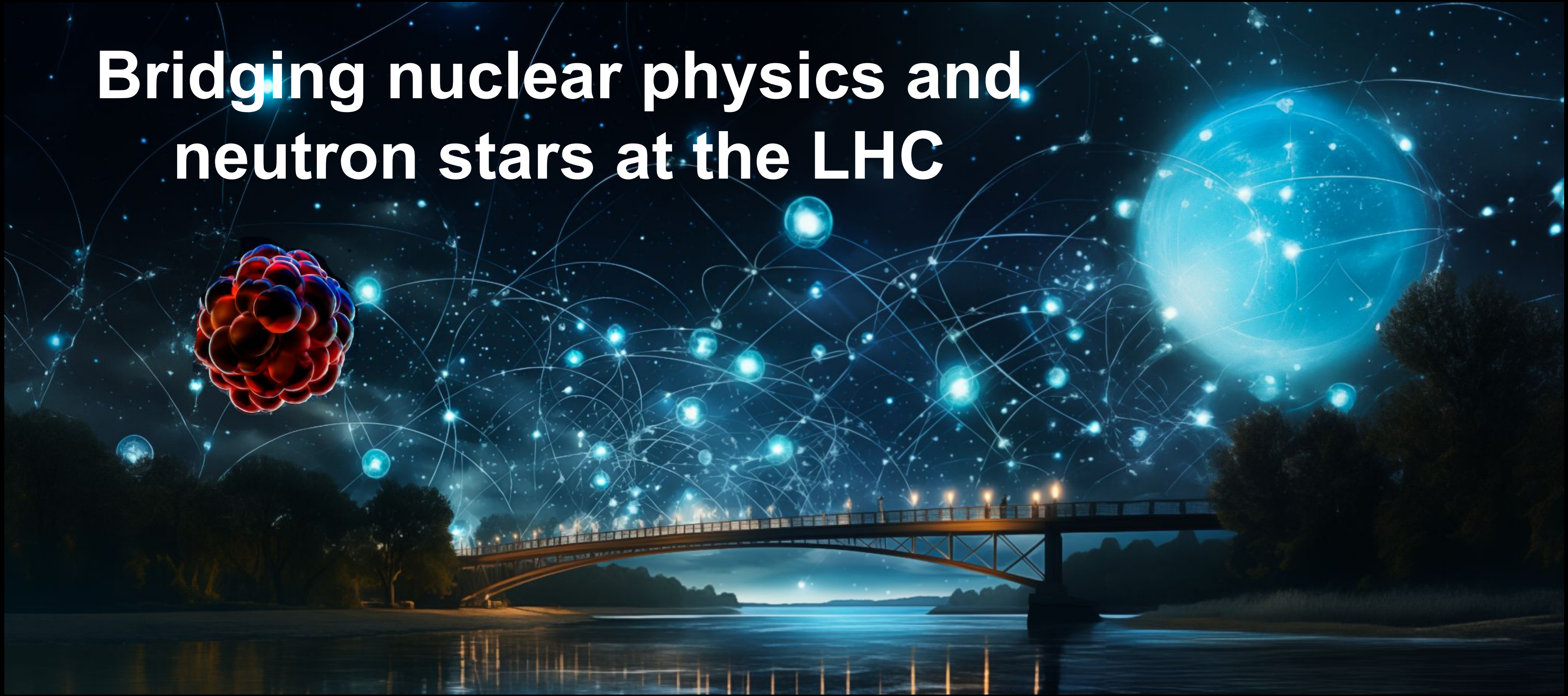
Sofia University
St. Kliment Ohridski

Bridging nuclear physics and neutron stars at the LHC



Dimitar Mihaylov @ CosmicWISPers 2025 (cost action)

Special thanks to L. Fabbietti, J. Haidenbauer, V. Mantovani Sarti and Isaac Vidaña

10th September 2025, Sofia, Bulgaria

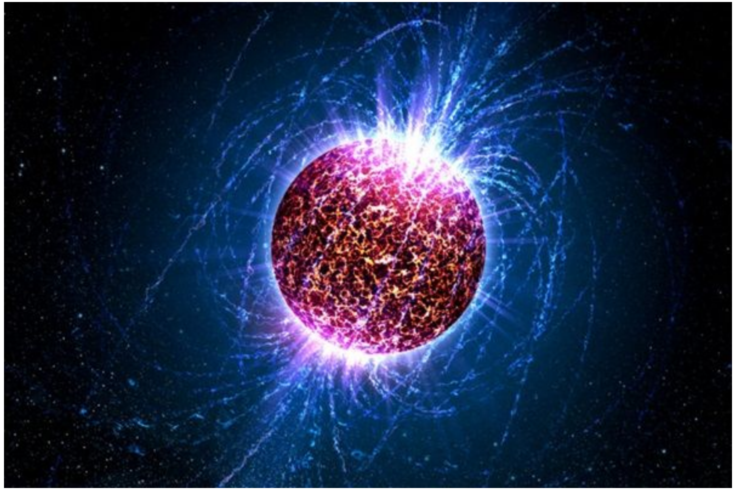
PLB 850 (2024), 138550
EPJA 61 (2025), 3, 59

Neutron stars (NS)

Very compact, very dense
The sun packed in Manhattan

Radius: R ~ 10 km
Mass: M ~ 2 solar masses ($M_\odot$)
Density: few times ρ_0*)

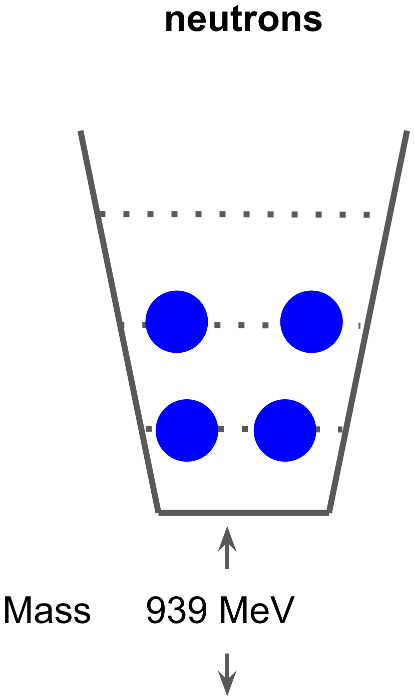
*) ρ_0=0.16 fm^{-3} is the density of the nucleus of an atom, called “nuclear saturation density”.

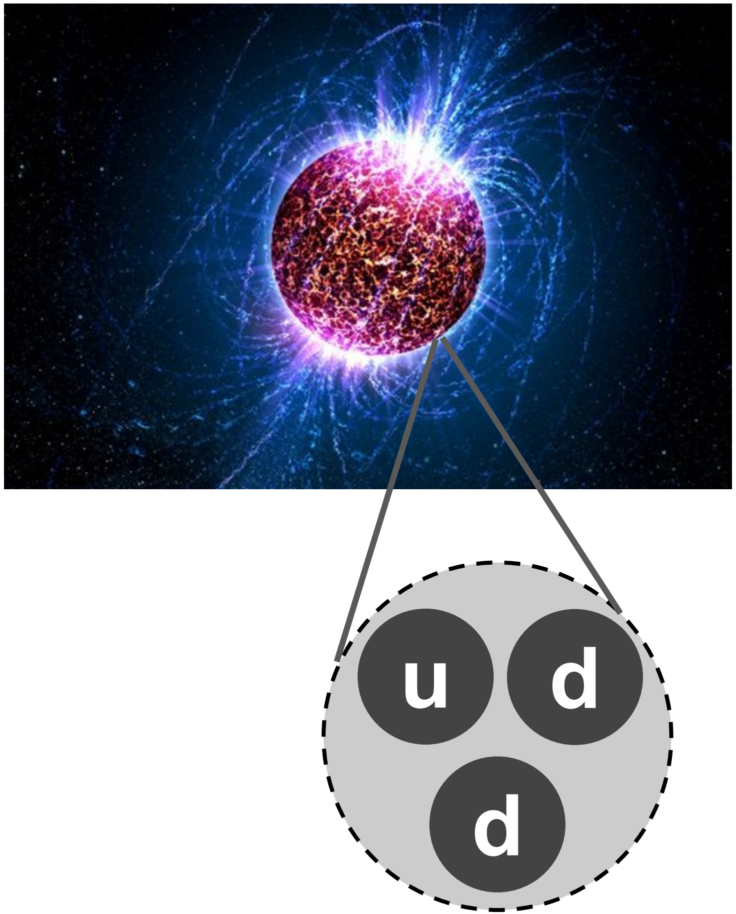


What is inside?

Neutron stars (NS)

Composition

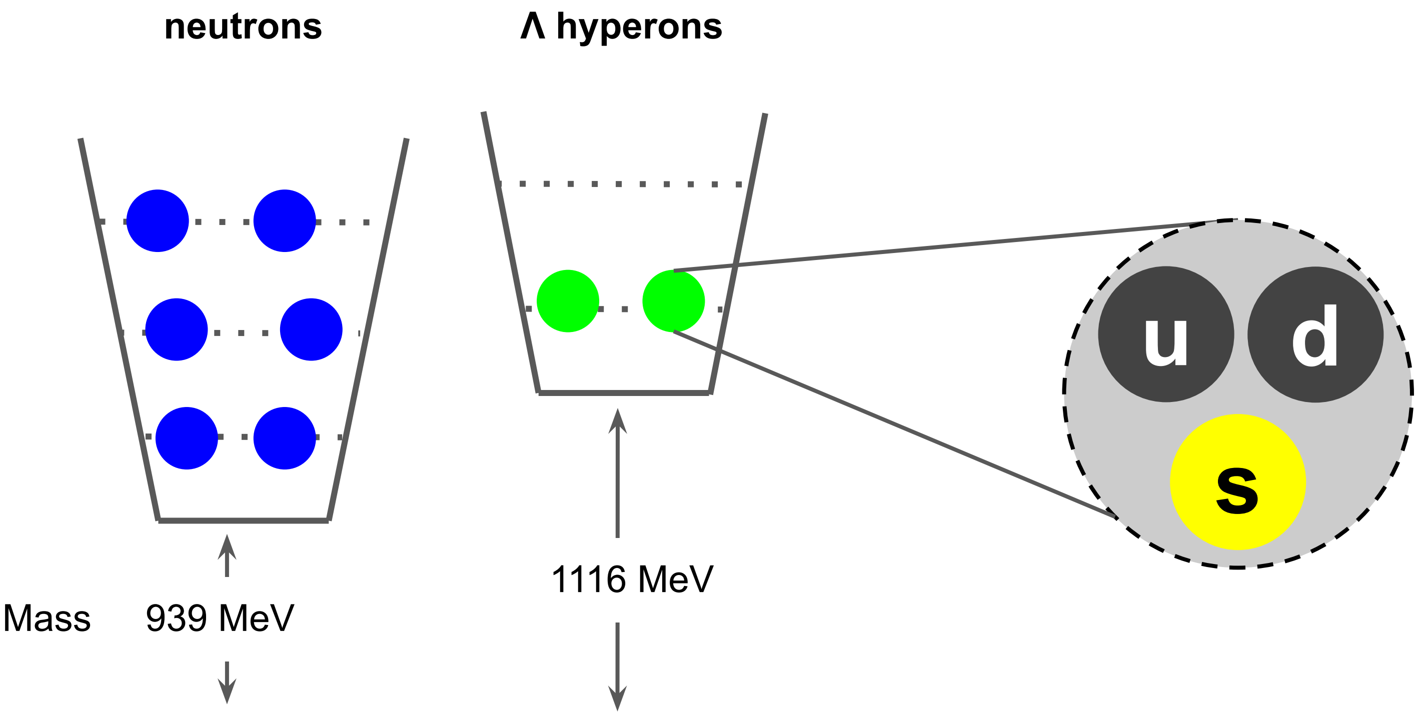




Neutron stars (NS)

Composition

- As density increases, it might become **possible to form hyperons.**
  N.B. This depends on the chemical potential, i.e. sum of Fermi energy and the effective in-medium mass of the particles.



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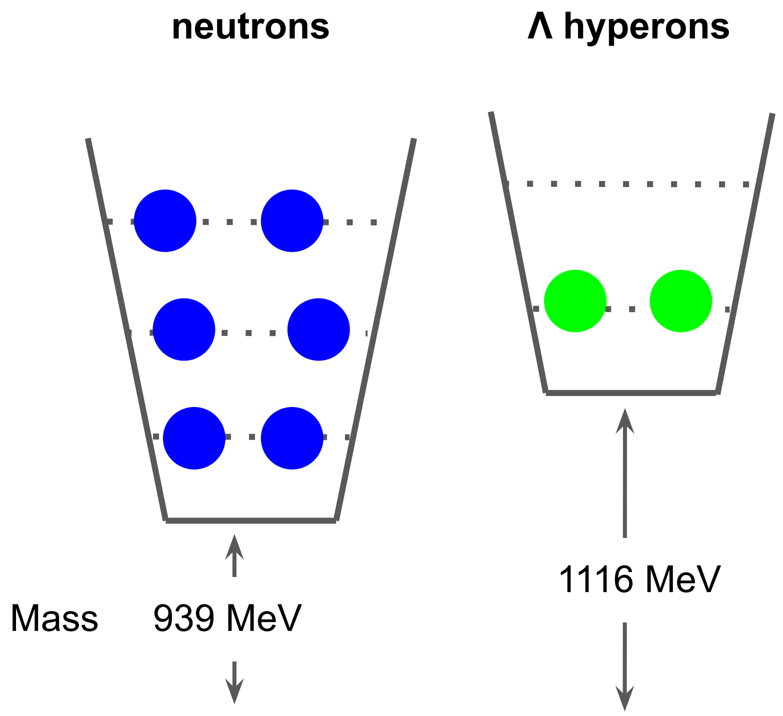

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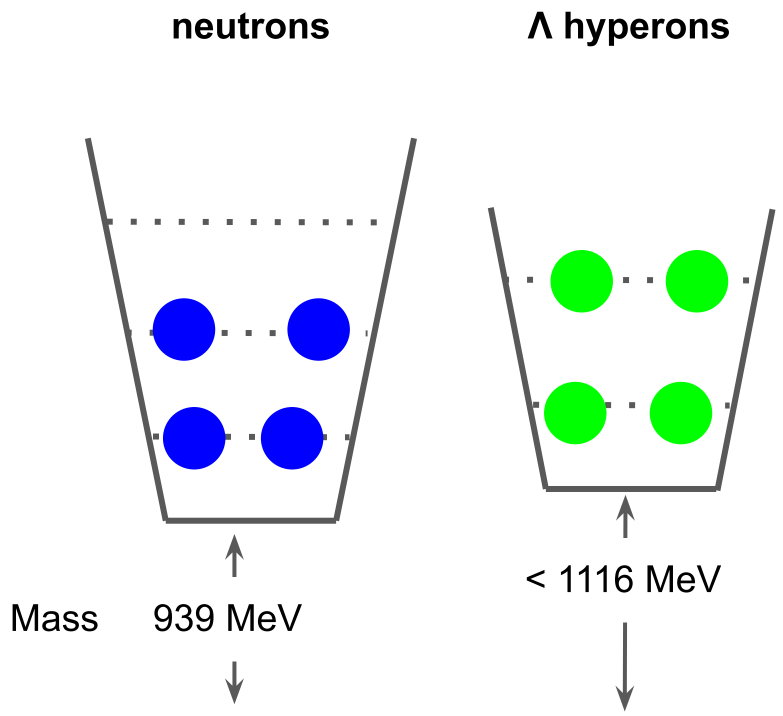

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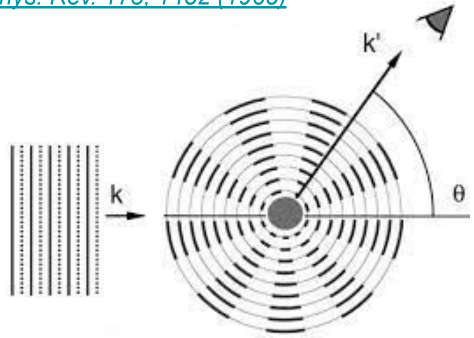
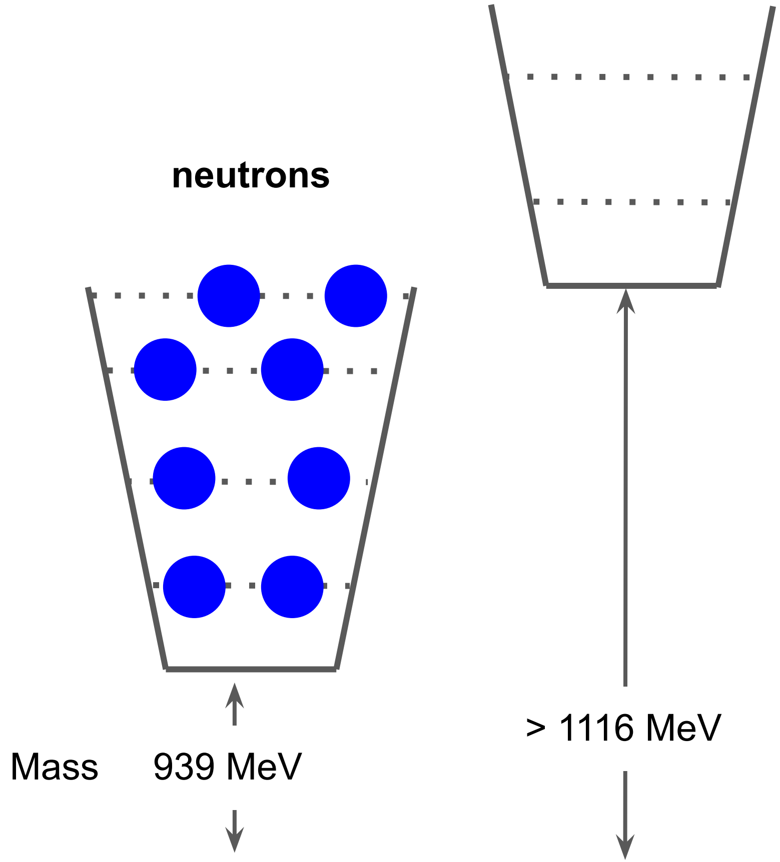
- Their effective **in-medium mass (and potential U_Λ) depends on the interaction** with the surrounding particles
- **Attractive NΛ interaction**.
  Known from e.g. scattering experiments

Sechi-Zorn et al. *Phys. Rev. 175, 1735 (1968)*
Alexander et al. *Phys. Rev. 173, 1452 (1968)*



Neutron stars (NS)

Composition



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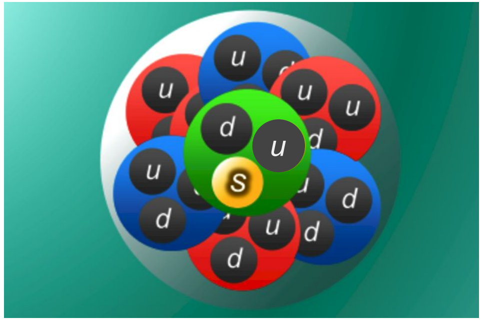
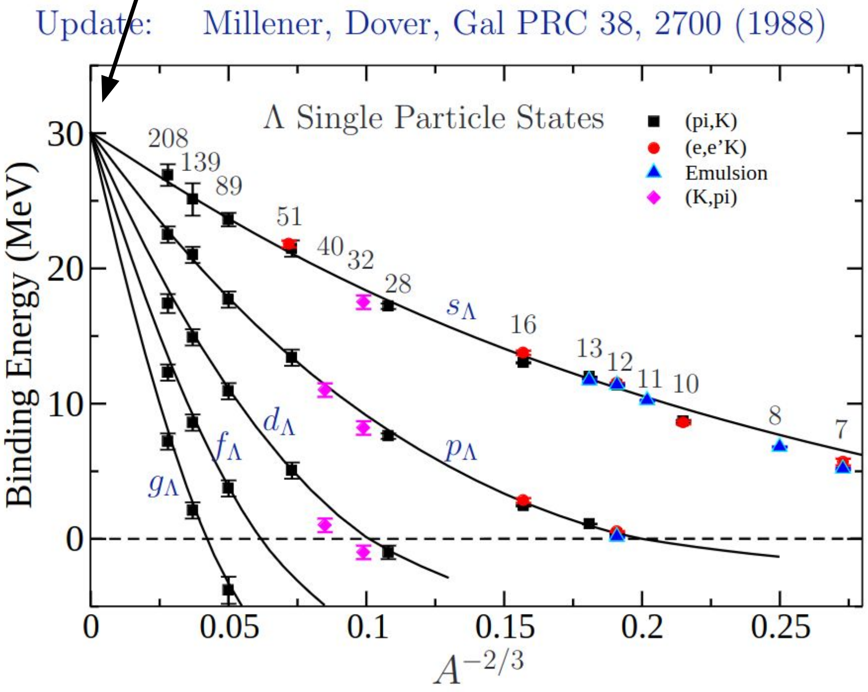
- **Repulsion**, e.g. due to many- (three-) body forces, may prohibit their formation.
  In agreement with hypernuclei experiments.



Hashimoto and Tamura, *Prog. Part. Nucl. Phys., 57:564–653, 2006*

In-medium **UΛ(ρ)** potential

UΛ @ ρ_0 ≈ −30 MeV



[Friedman and Gal, *Nucl.Phys.A 1039 (2023) 122725*]

- As density increases, it might become **possible to form hyperons.**
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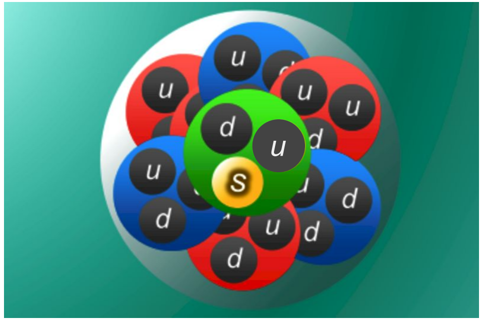
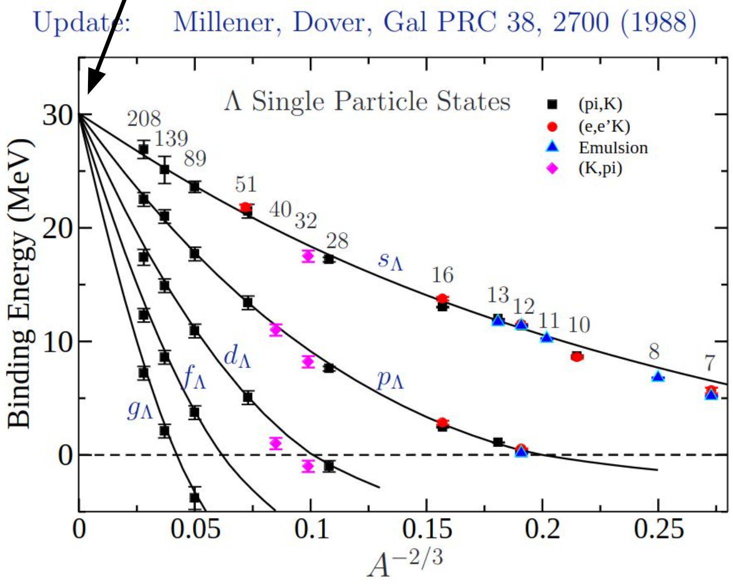


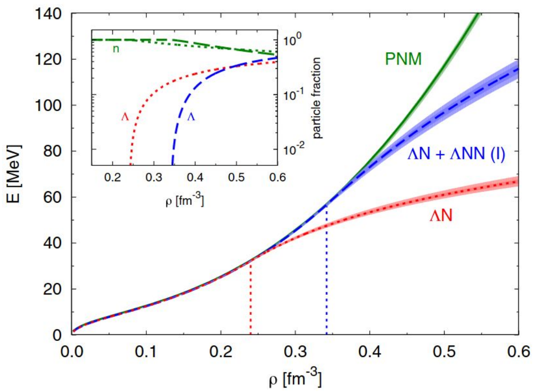
[Hashimoto and Tamura, *Prog. Part. Nucl. Phys., 57:564–653, 2006*]

Connection to astrophysics

UΛ @ ρ0 ≈ −30 MeV

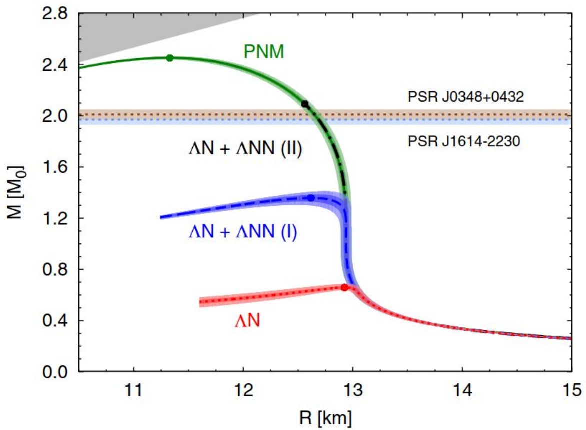


Friedman and Gal, *Nucl.Phys.A 1039 (2023) 122725*



Obtain an EoS

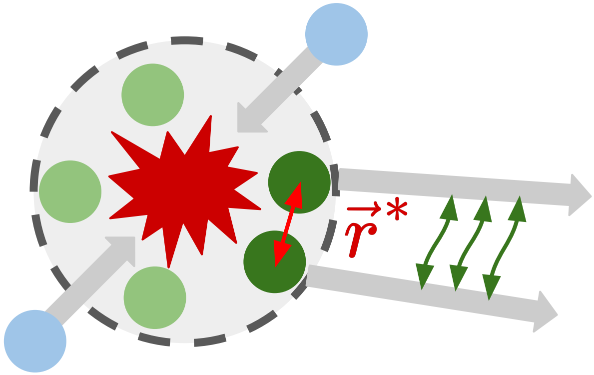
Lonardoni et al.
Phys.Rev.Lett. 114 (2015) 9, 092301



Convert it into mass/radius relation of neutrons stars

Femtoscopy

Overview (2-body)



Femtoscopy

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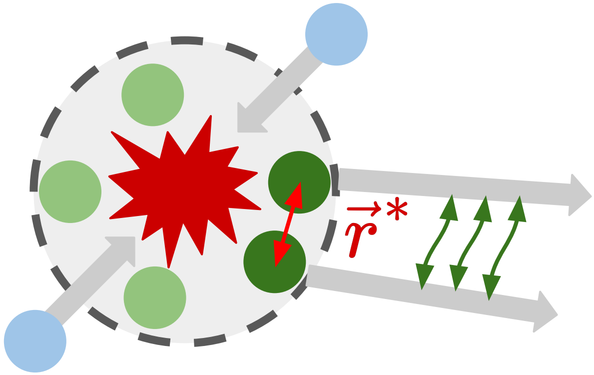
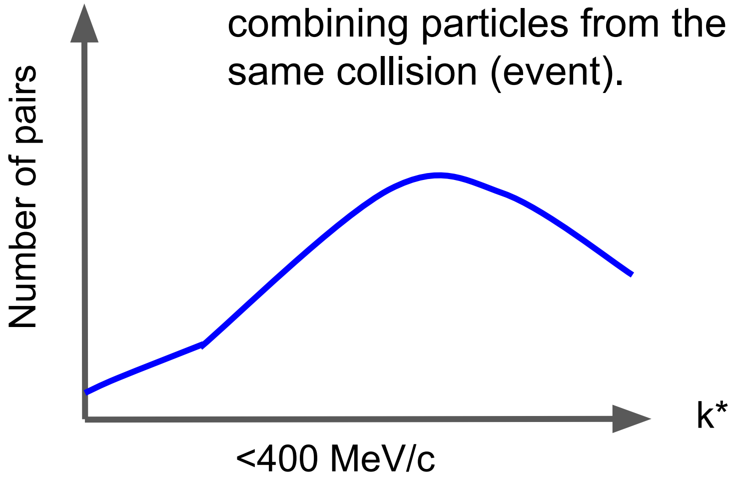
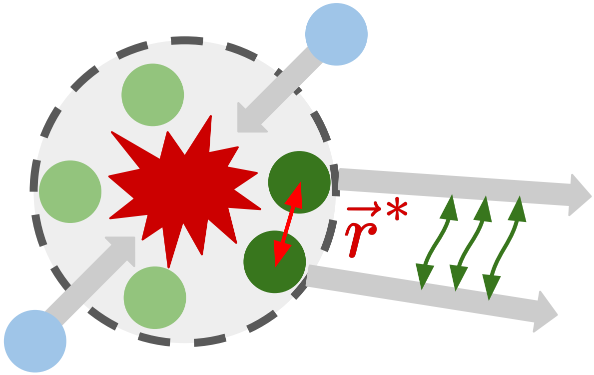


- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).



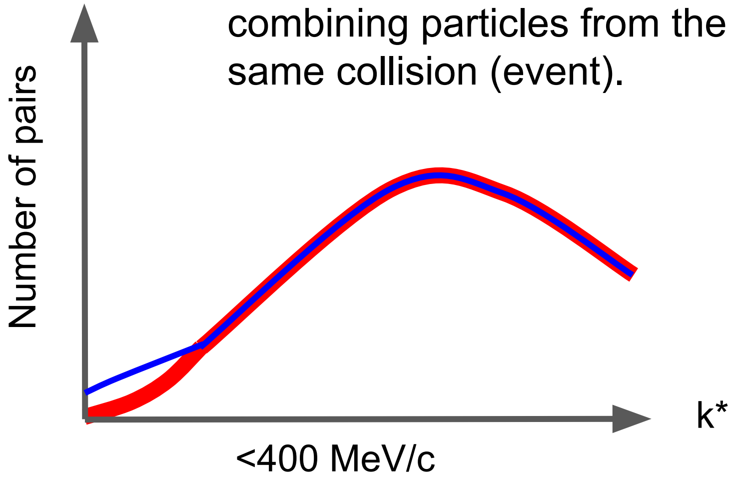
Femtoscopy

Overview (2-body)



- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).

- ***Mixed event sample (ME)*:** Uncorrelated pairs, obtained by combining particles from two different collisions (events).



Femtoscopy

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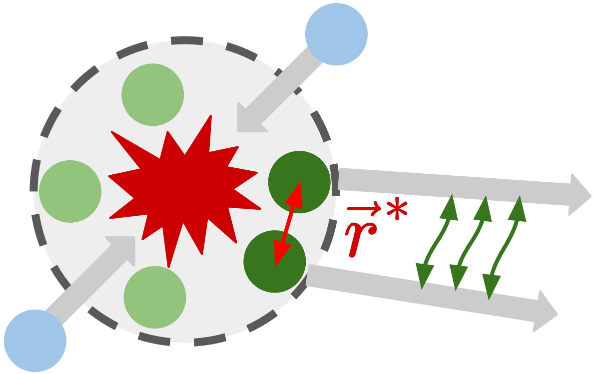
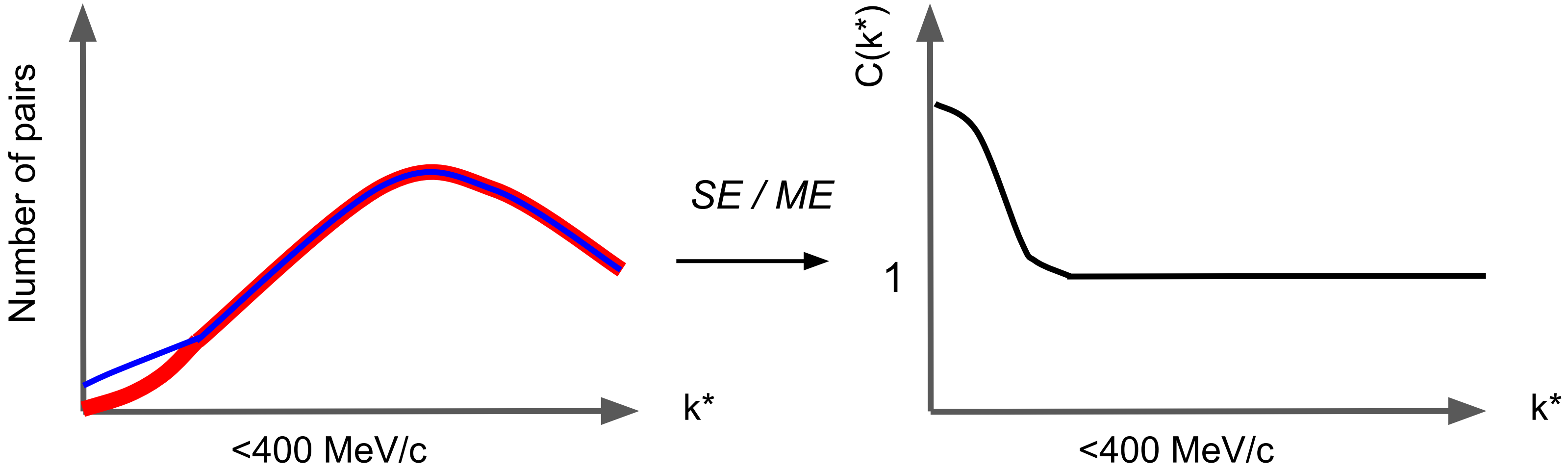


- The ***correlation function C(k*)*** = *SE / ME*, ideally equal to unity in the absence of any correlations.



Femtoscopy

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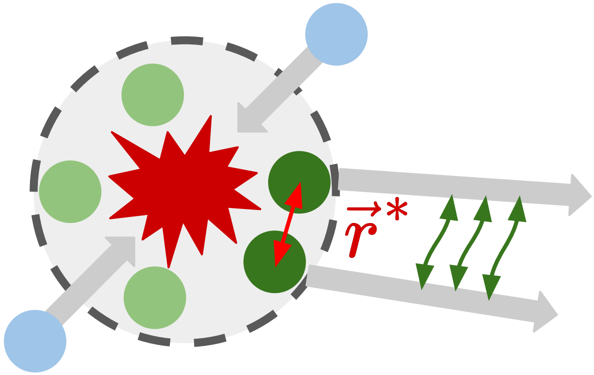
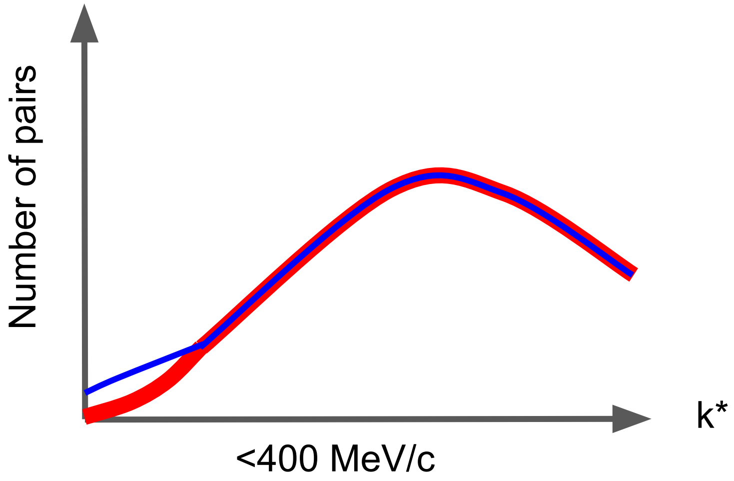
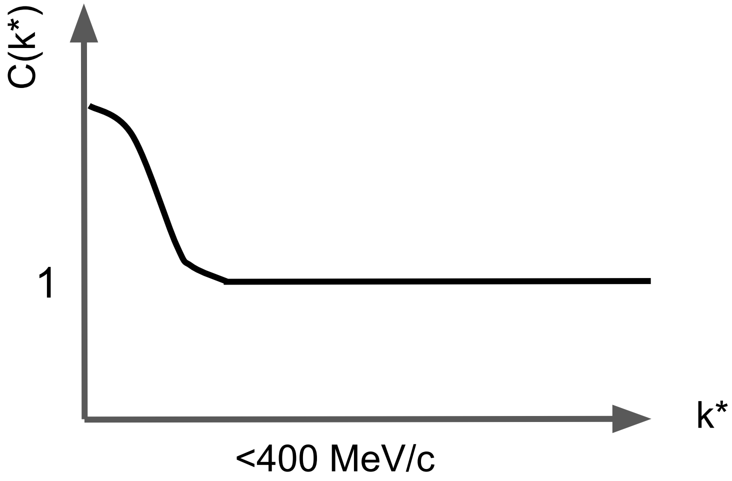


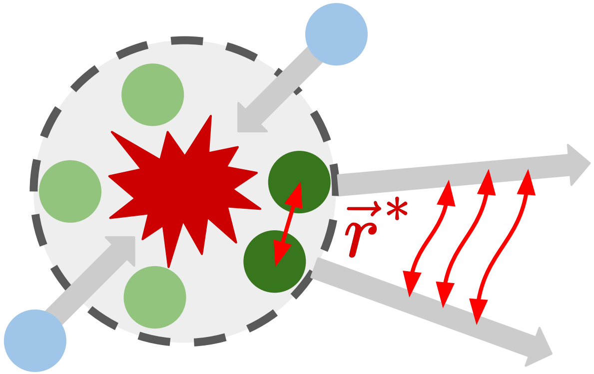
- **Attractive** final state interaction (FSI)



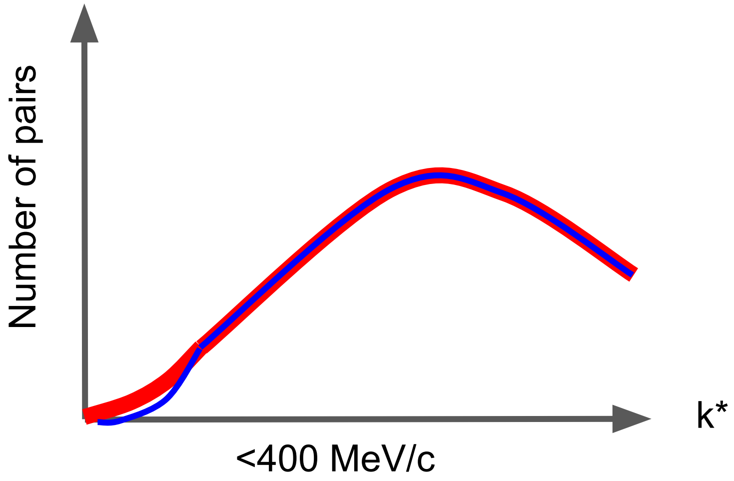


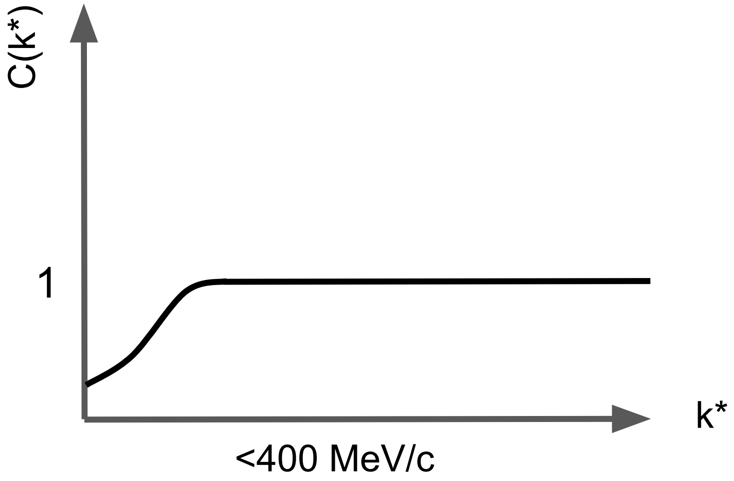
Femtoscopy

Overview (2-body)



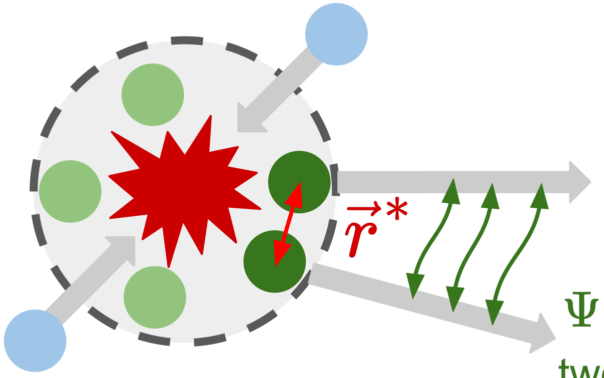
- **Repulsive** final state interaction (FSI).





Femtoscopy

Koonin-Pratt equation



$$C(k^*) = \frac{N_{\mathrm{SE}}(k^*)}{N_{\mathrm{ME}}(k^*)} = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

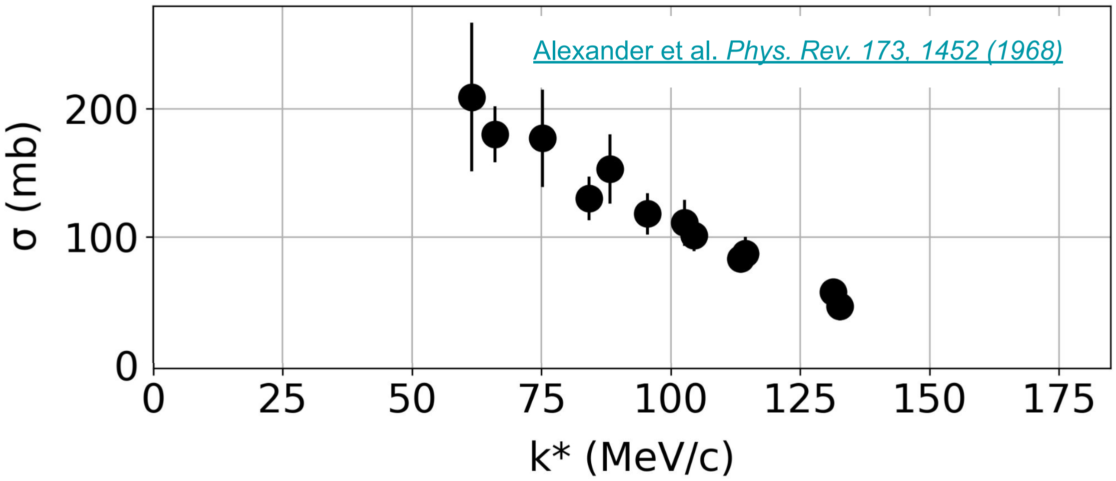
Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*

Relative distance and ½ relative momentum evaluated in the pair rest frame

- Measure C(k*), fix S(r*), study the interaction.
- Detailed studies of the source in pp:
  ALICE Coll. *Phys.Lett.B 811 (2020) 135849*
  Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590
- CATS framework to evaluate the above integral Mihaylov et al. *EPJC* 78 (2018) 5, 394

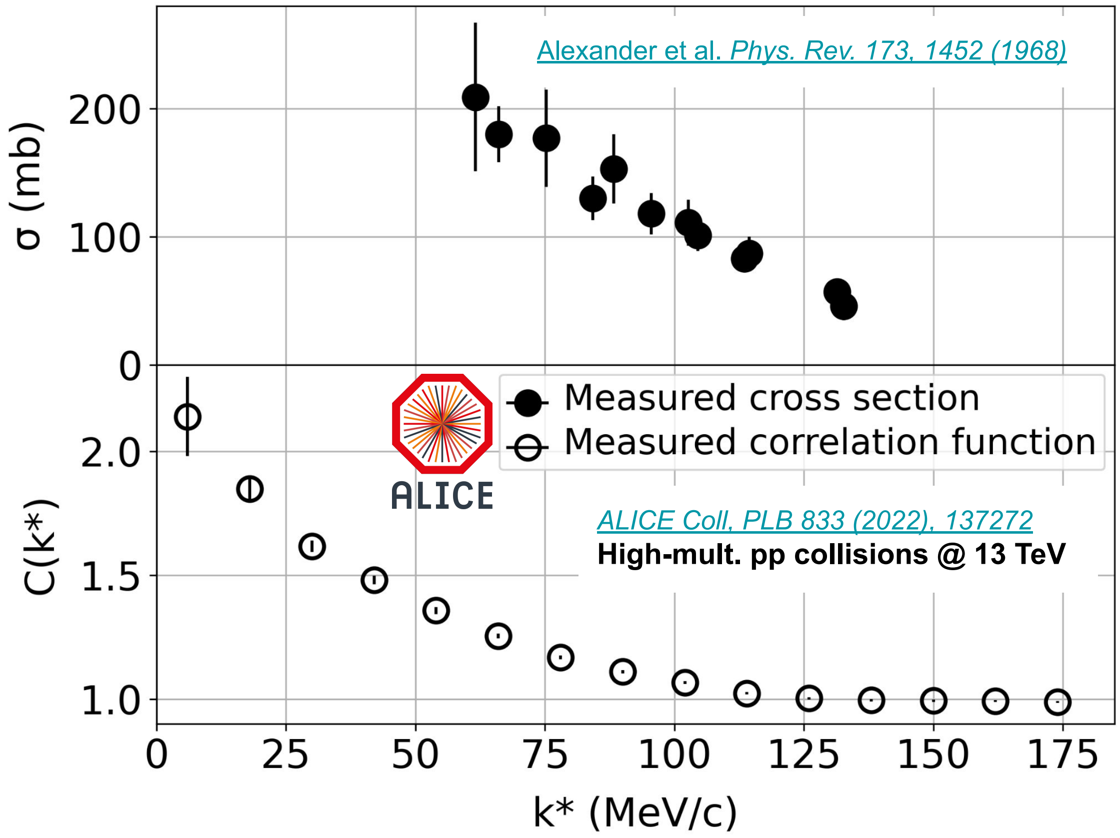
Data on pΛ

Cross section and correlation function



Data on pΛ

Cross section and correlation function

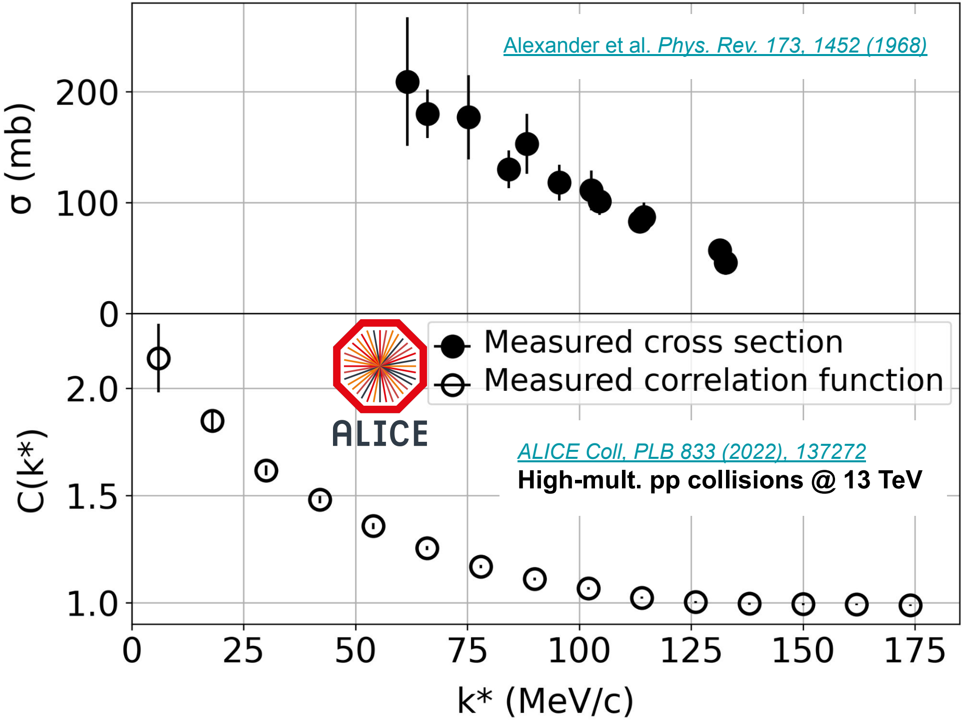


Superior low-energy reach and uncertainties of the ALICE data

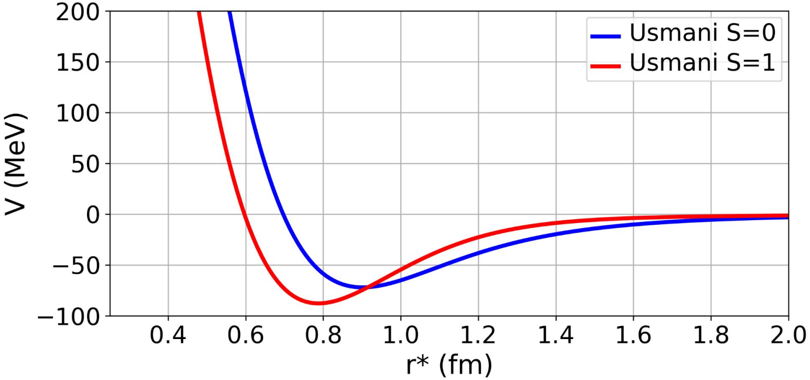
N.B. Both observables contain ¼ S=0 and ¾ S=1

The present study: pΛ

Combine cross section and correlation function



Potential: Usmani et al, PRC, 29:684–687, 1984



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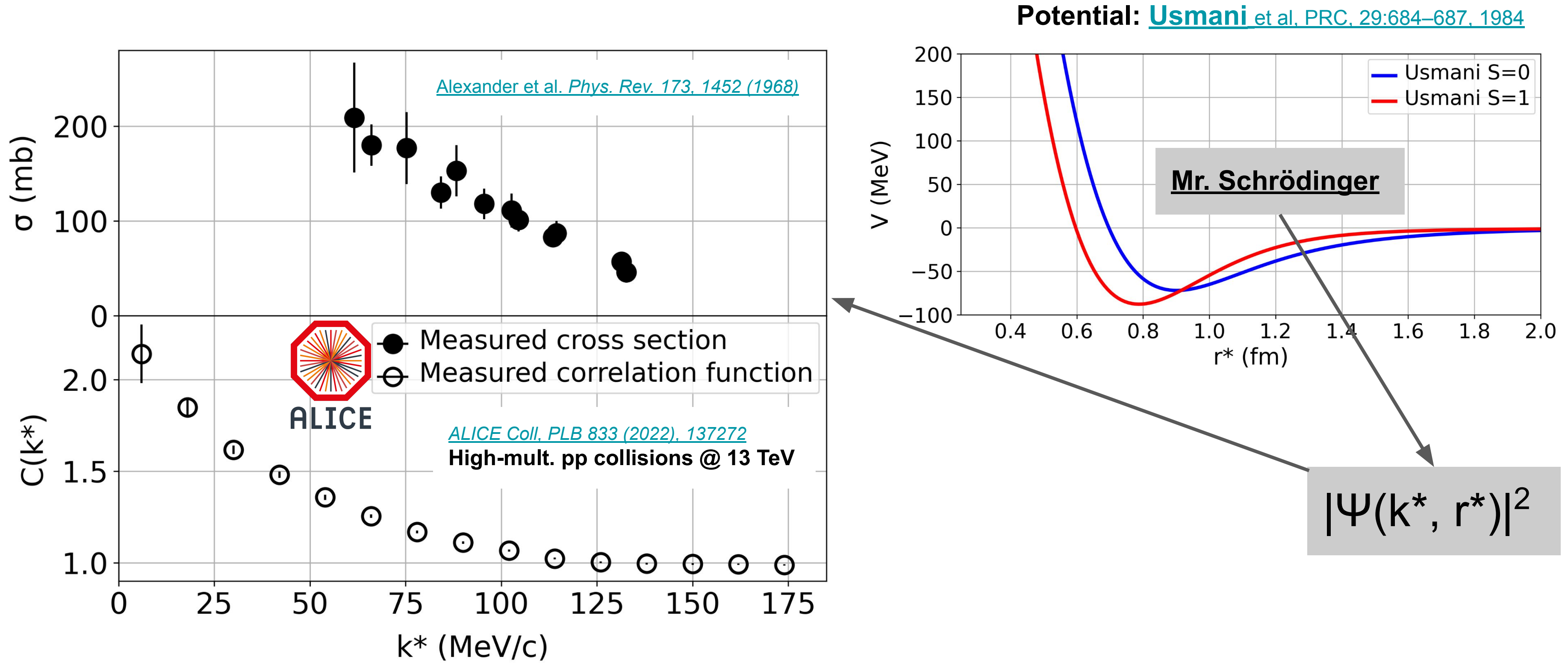

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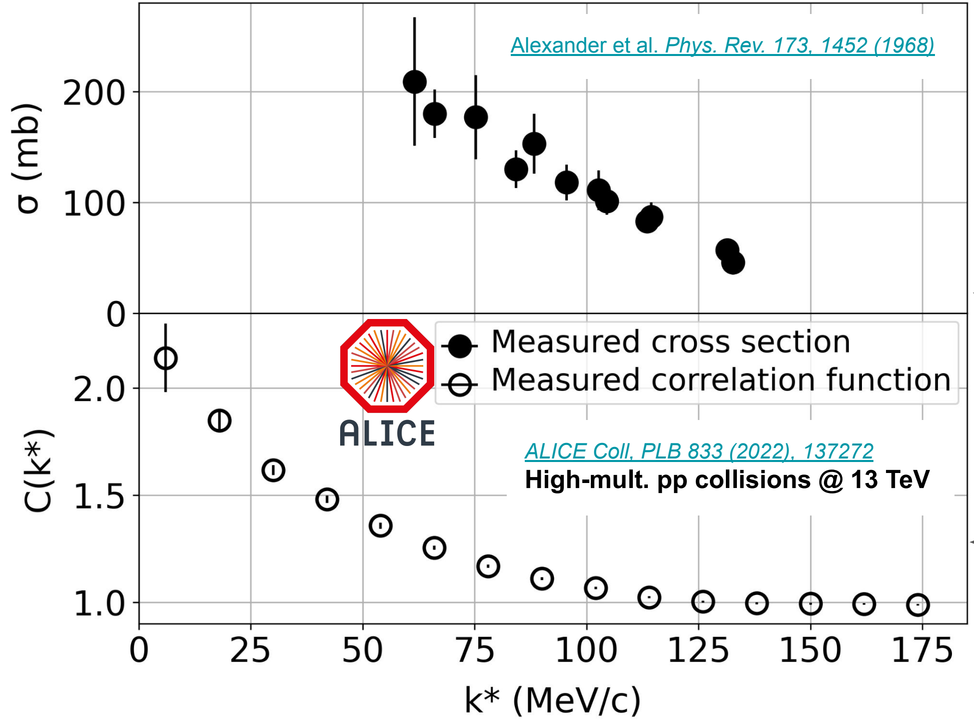

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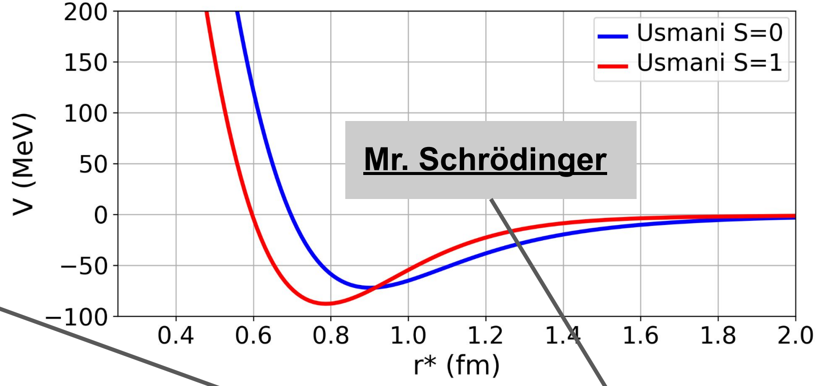


Mr. Schrödinger

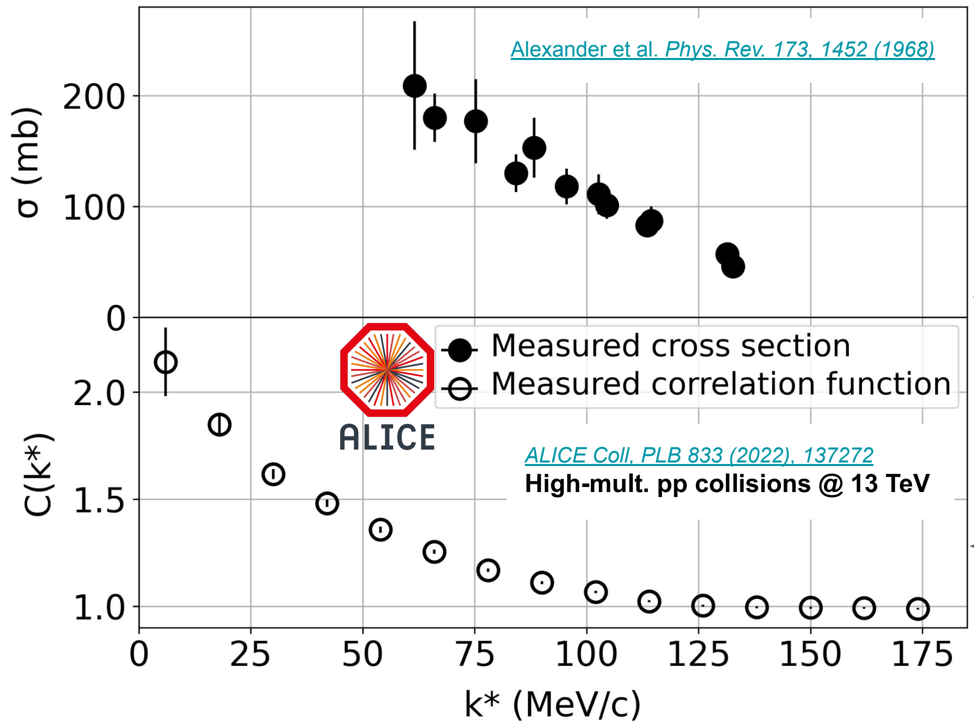
$|\Psi(k^*, r^*)|^2$

Magic of femtoscopy:

Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*

The present study: pΛ

Combine cross section and correlation function



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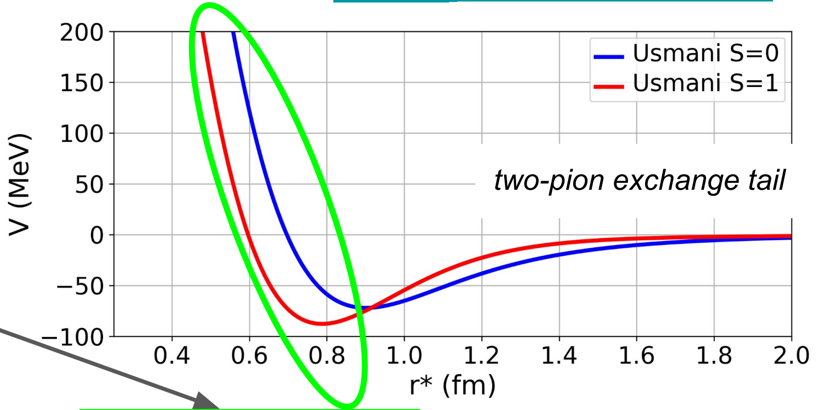
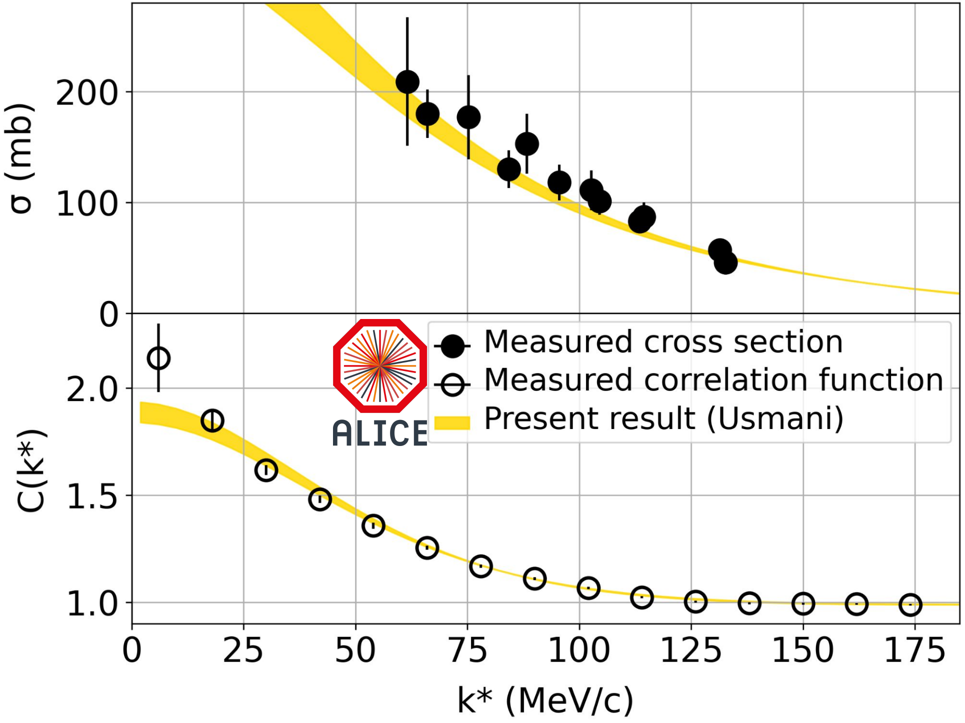


Phenomenological repulsive core

FIT

The present study: pΛ

Comparison of the results to data



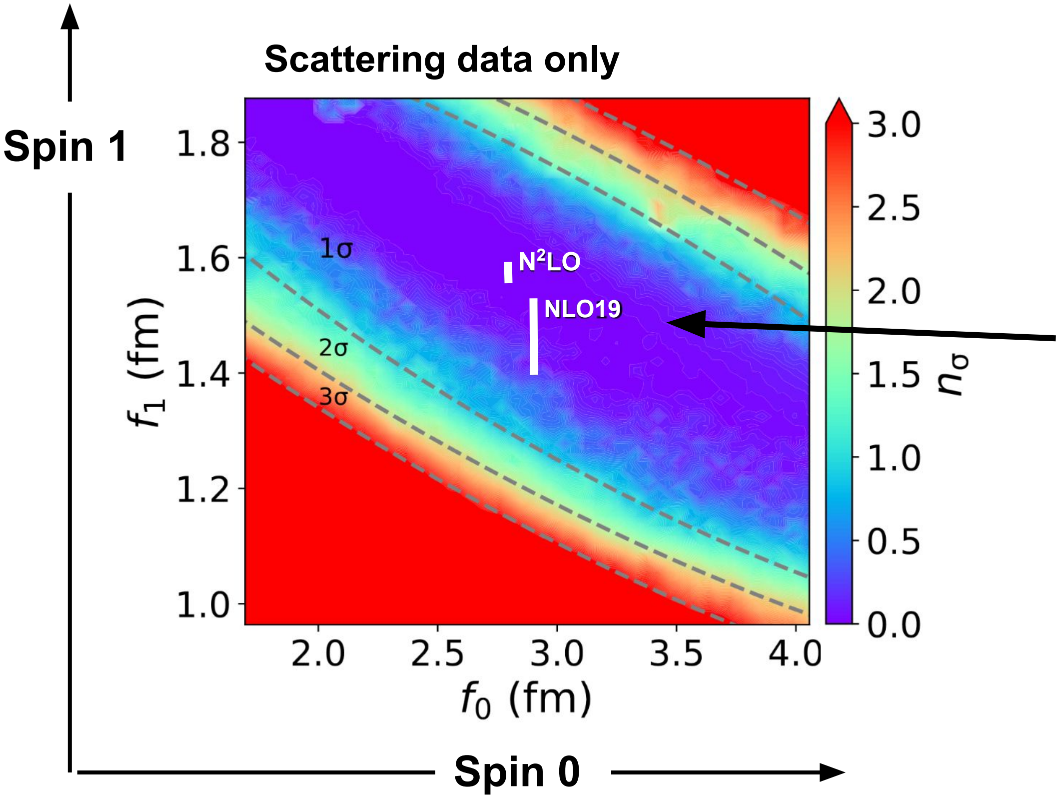
Disclaimer: the data is fitted differentially, for details:

[Mihaylov, Haidenbauer and Mantovani Sarti, PLB 850 (2024), 138550]

[Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590]

Scattering length

PLB 850 (2024), 138550

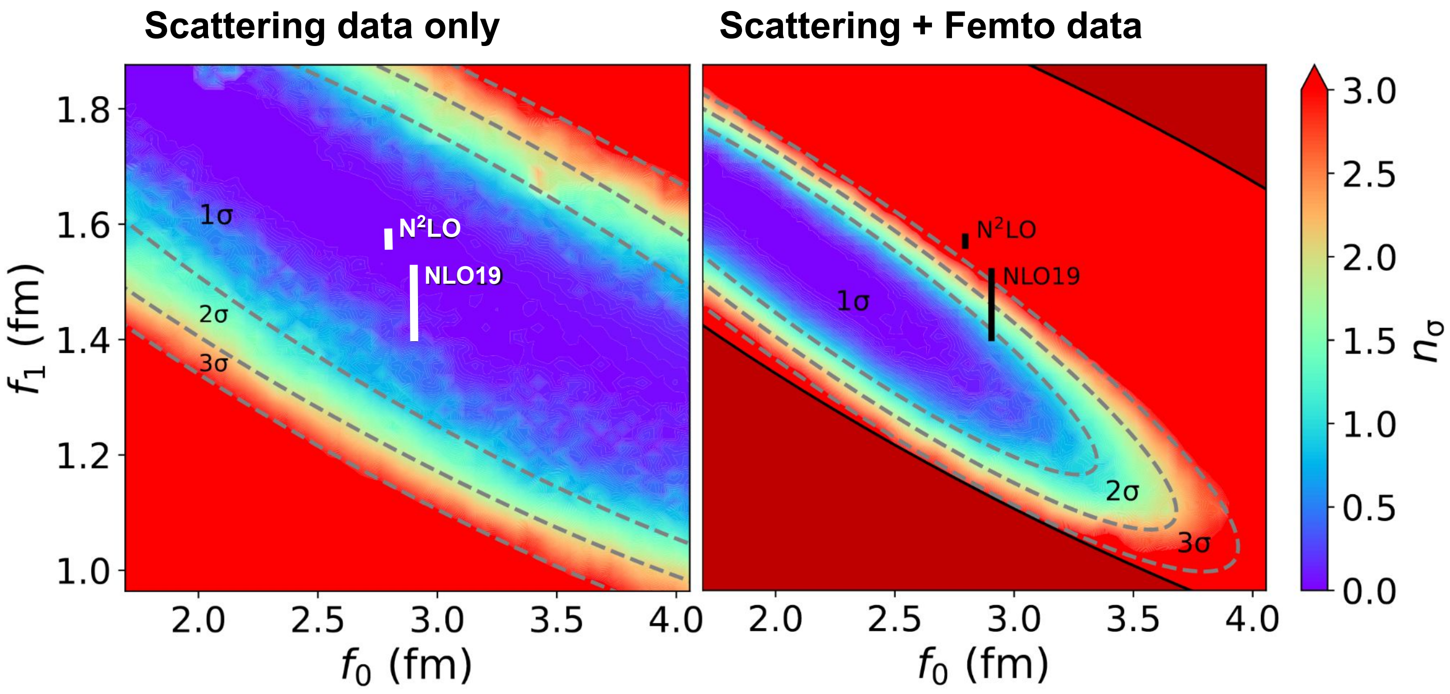


Values from chiral effective field theory (χEFT), which is presently constrained to the scattering data.

Scattering length

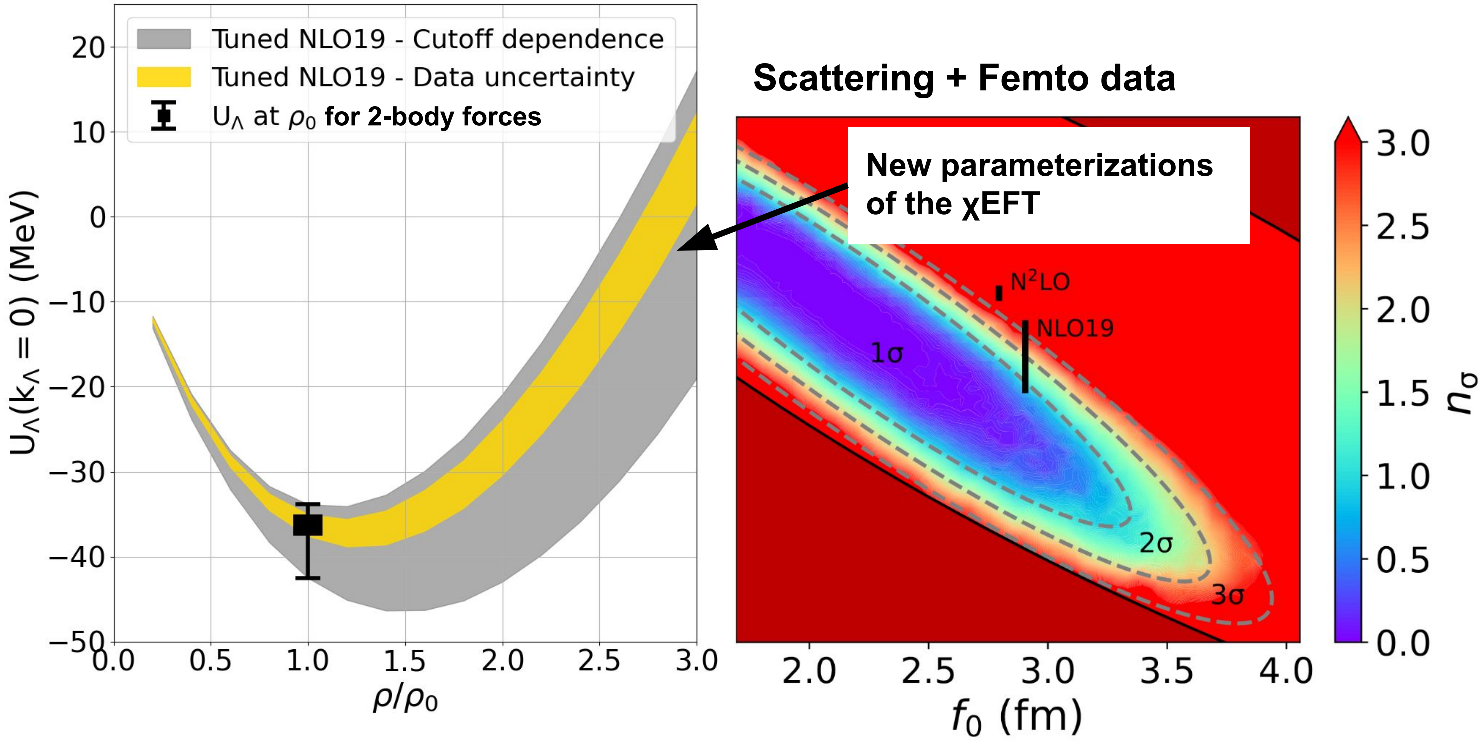
PLB 850 (2024), 138550

NEW



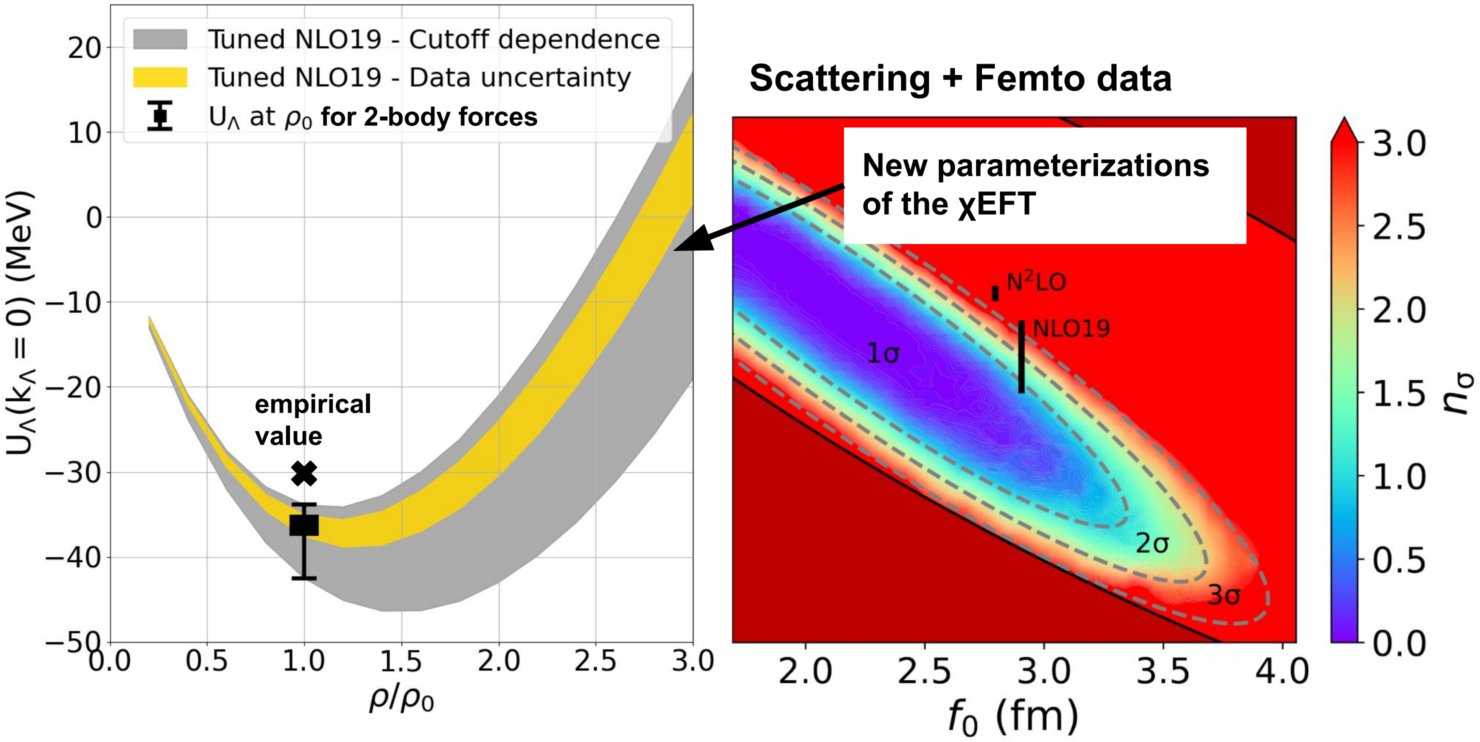
In-medium **UΛ(ρ)** potential

PLB 850 (2024), 138550



In-medium $U_\Lambda(\rho)$ potential

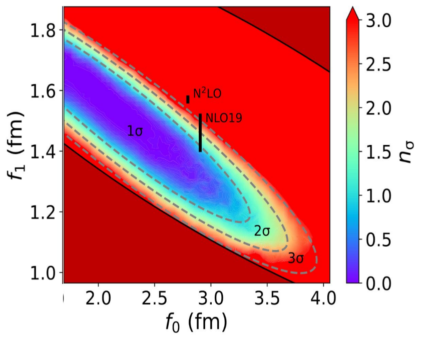
PLB 850 (2024), 138550



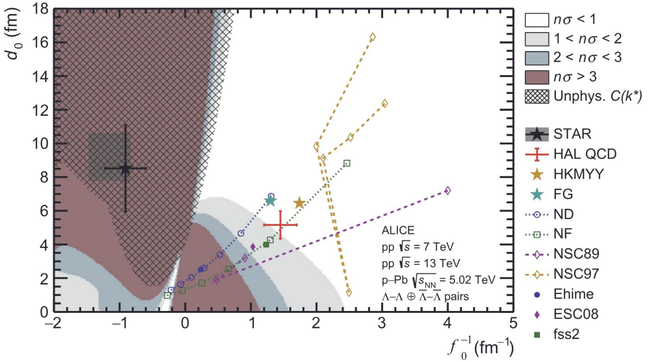
- A result compatible with repulsive 3-body forces

What about the EoS?

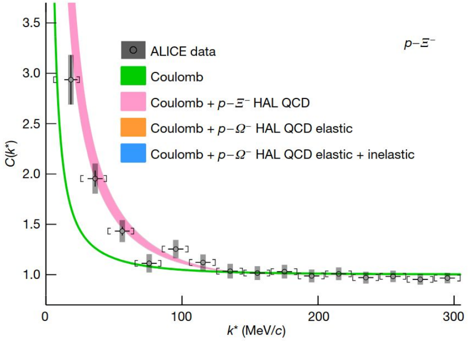
Let’s use all we have



[*Mihaylov et al, PLB 850 (2024), 138550*](#)
Modelling of pΛ by χEFT



[ALICE Coll, PLB 797 (2019) 134822](#)
Good description by HAL QCD potentials:
[HAL QCD Coll, Nucl.Phys.A 998 121737, 2020](#)



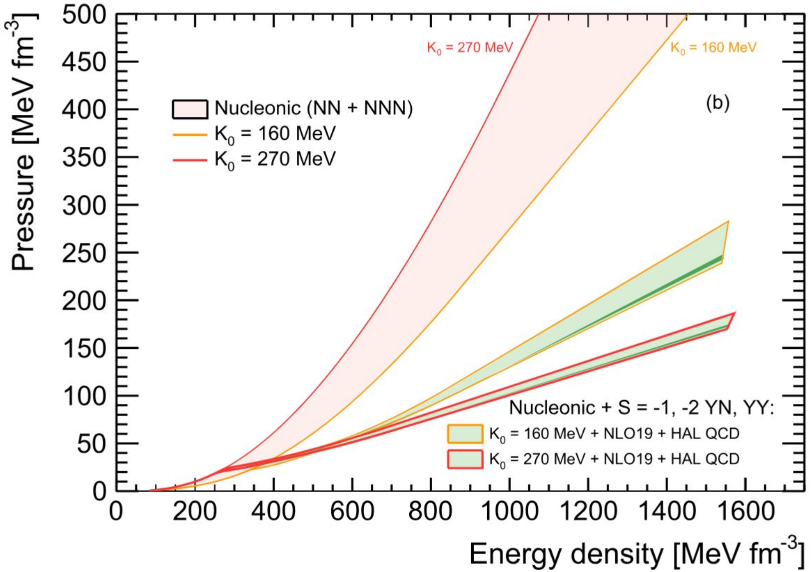
[ALICE Coll, Nature 588 232-238, 2020](#)
Good description by HAL QCD potentials:
[HAL QCD Coll, Nucl.Phys.A 998 121737, 2020](#)

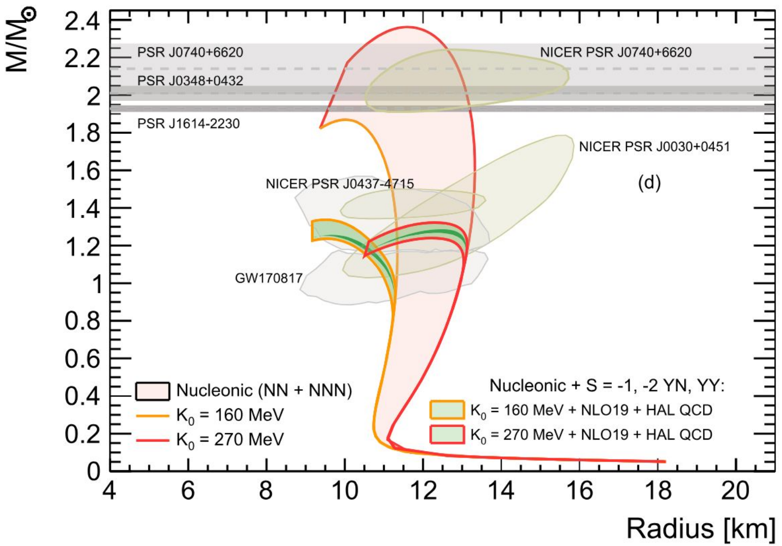
- Take available (femto) data on the Λ and Ξ interaction.
  pΣ0 data available but low statistical significance
  Preliminary ALICE results on pΣ+ available but not used in this analysis
- A Brueckner–Hartree–Fock (BNF) approach adopted by ***Isaac Vidaña***, using potentials from the theories describing the ALICE data, to construct the EoS.
- Adopt the Tolman–Oppenheimer–Volkoff to evaluate the corresponding mass-radius relation for neutron stars.
  [*I. Vidana et al, EPJA 61 (2025), 3, 59*](#)

Results

I. Vidana et al, EPJA 61 (2025), 3, 59

Instead of a summary





- State of the art data and models are unable to describe the existence of heavy NS. **The hyperon puzzle remains an open question!**
- Possible solutions introduce additional repulsion, e.g. three body forces.
- A more exotic solution is proposed by introducing QCD axions in neutron stars.
  e.g. talks by Jaime Ruz, Marco Regis, Konstantin Springmann, Francesca Lecce

BACKUP

Where to now (with ALICE)?

- The ongoing data taking period (RUN 3) at the LHC will lead to significant increase in statistics in all measured systems. Some new systems will become accessible.
- Dedicated online triggers will lead to orders of magnitude improvements on targeted analysis, such as three-body correlations.
- Stay tuned for the results that will be made public at QM next week.

Where to now (with ALICE): Three body

- The ongoing data taking period (RUN 3) at the LHC will lead to significant increase in statistics in all measured systems. Some new systems will become accessible.
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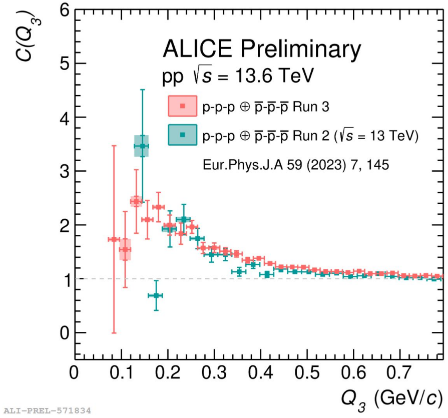
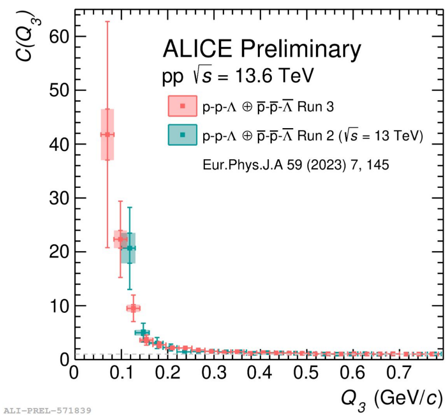
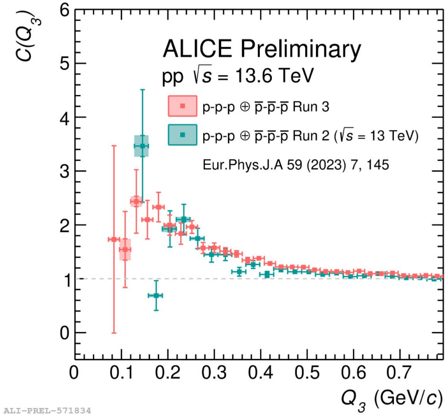


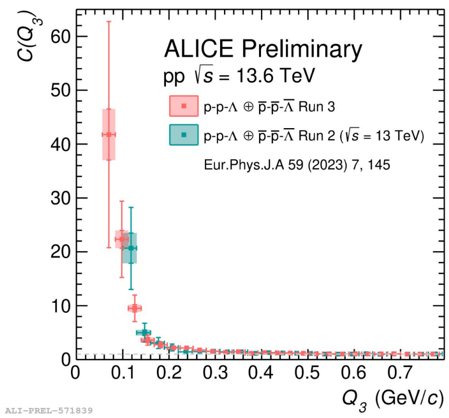


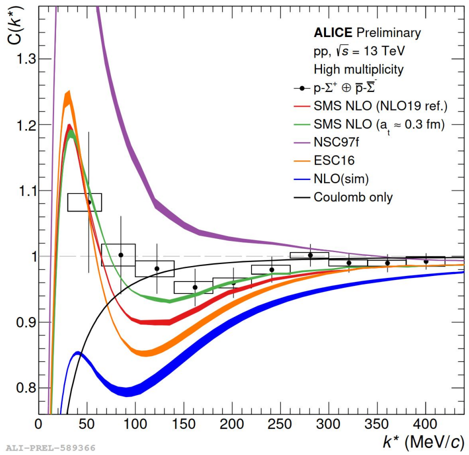
RUN 2 results: ALICE Coll, *EPJA 59 (2023) 7, 145*
For updated RUN 3 data and comparison to models follow the talk of L. Sersknyte at QM 2025
State of the art of the modeling in:
Kievsky et al, PRC 109 (2024) 3, 034006
Garrido et al, PRC 110 (2024) 5, 054004

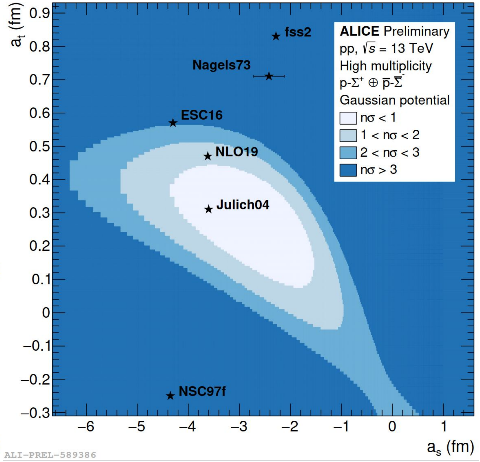
Where to now (with ALICE): Three body and more

- The ongoing data taking period (RUN 3) at the LHC will lead to significant increase in statistics in all measured systems. Some new systems will become accessible.
- Dedicated online triggers will lead to orders of magnitude improvements on targeted analysis, such as three-body correlations.
- Stay tuned for the results that will be made public at QM next week.









RUN 2 results: ALICE Coll, *EPJA 59 (2023) 7, 145*
For updated RUN 3 data and comparison to models follow the talk of L. Sersknyte at QM 2025
State of the art of the modeling in:
Kievsky et al, PRC 109 (2024) 3, 034006
Garrido et al, PRC 110 (2024) 5, 054004

New measurements of pΣ+ will be presented at a QM poster by B. Heybeck

The take-home message

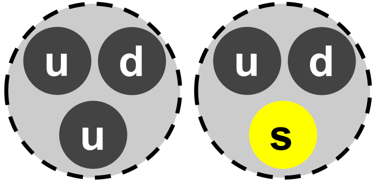
We need be actively collaborating, between theory and experiment, but also between different types of complementary experiments.

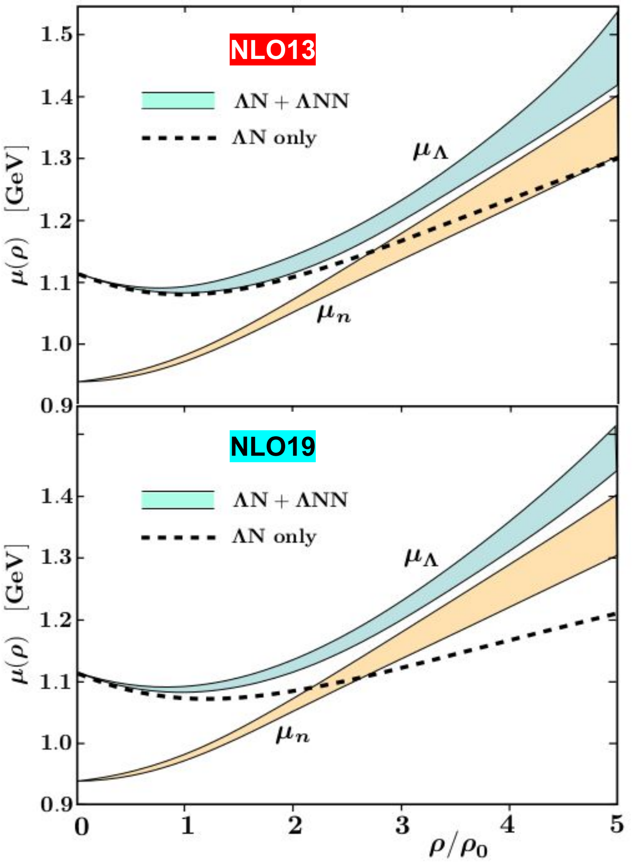
And we already have one fantastic example for that in the NΛ-NΣ sector:

- Femtoscopy constraints for pΛ and now pΣ+ at low energies
  ALICE Coll. *PLB 833 (2022), 137272*
- Scattering data a slightly higher energies in pΣ- and pΣ+
  K. Miwa et al, *PRL 128 (2022) 7, 072501*
  T. Nanamura et al, *EPJ Web Conf. 271 (2022) 04002*
- Theoretical implementations within χEFT
  Mihaylov et al, *PLB 850 (2024), 138550*
  J. Haidenbauer et al, *EPJA 59 (2023) 3, 63*
- Implications for the EoS and NS
  I. Vidana et al, *EPJA 61 (2025), 3, 59*
- And now challenging the three-body sector
  ALICE Coll, *EPJA 59 (2023) 7, 145*
  Kievsky et al, PRC 109 (2024) 3, 034006
  Garrido et al, PRC 110 (2024) 5, 054004
- And the list can be for sure expanded, e.g. by hypernuclei studies

pΛ interaction

Chiral effective field theory (χEFT)



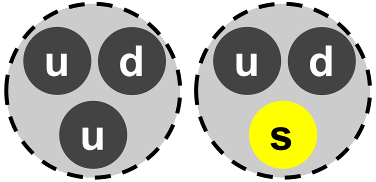


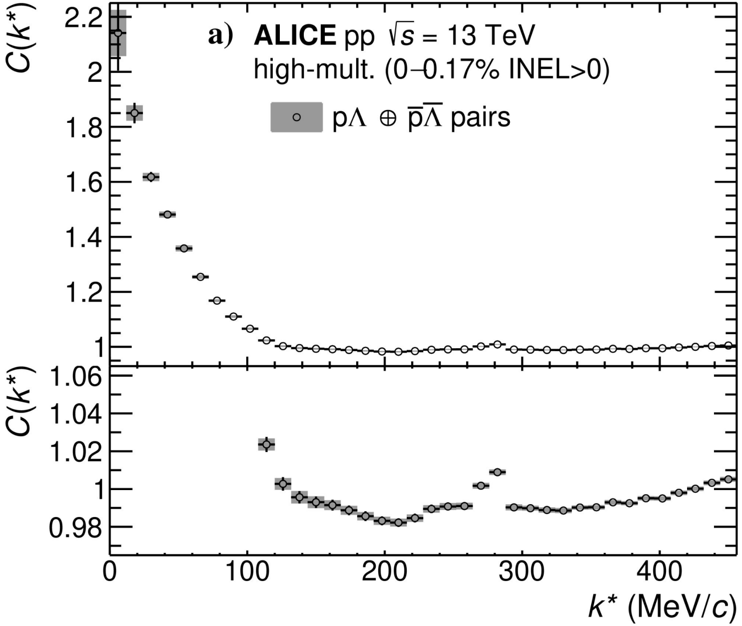
- The Next-to-Leading Order (NLO) calculation can be fine tuned to reproduce existing data using different parameters.
  Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*
- NLO13 has slightly stronger 2-body attraction in vacuum.
  NLO19 leads to stronger 3-body repulsion in-medium.
- Within this model, Λs cannot form inside neutron stars!
  This will explain the existence of measured massive neutron stars (M > 2 M⊙).
- **Experimental data is needed for both the 2-body and 3-body interaction** to obtain any quantitative conclusions.
  CLAS Coll. *PRL 127 (2021) 27, 272303*
  J-PARC E40 Coll. *PTEP 2022 (2022) 9, 093D01*
  ALICE Coll. *PLB 833 (2022), 137272*
  ALICE Coll. *EPJA 59 (2023) 7, 145*

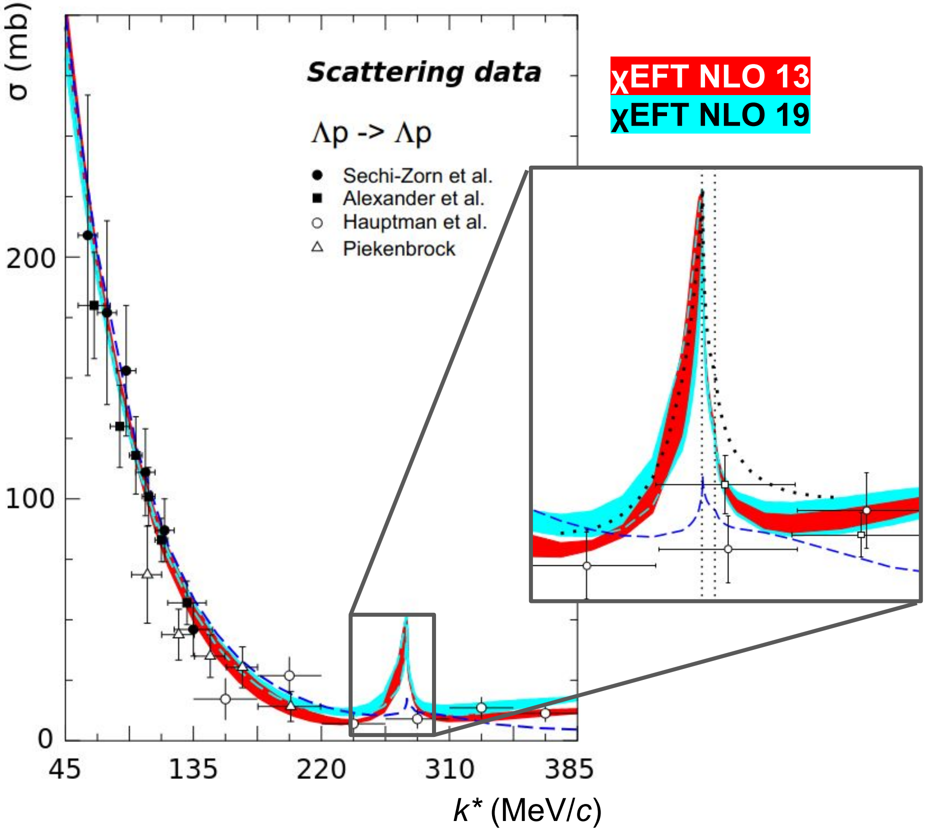
Gerstung et al. *Eur.Phys.J.A 56 (2020) 6, 175*

pΛ interaction

The femto era begins!



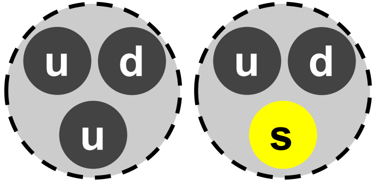


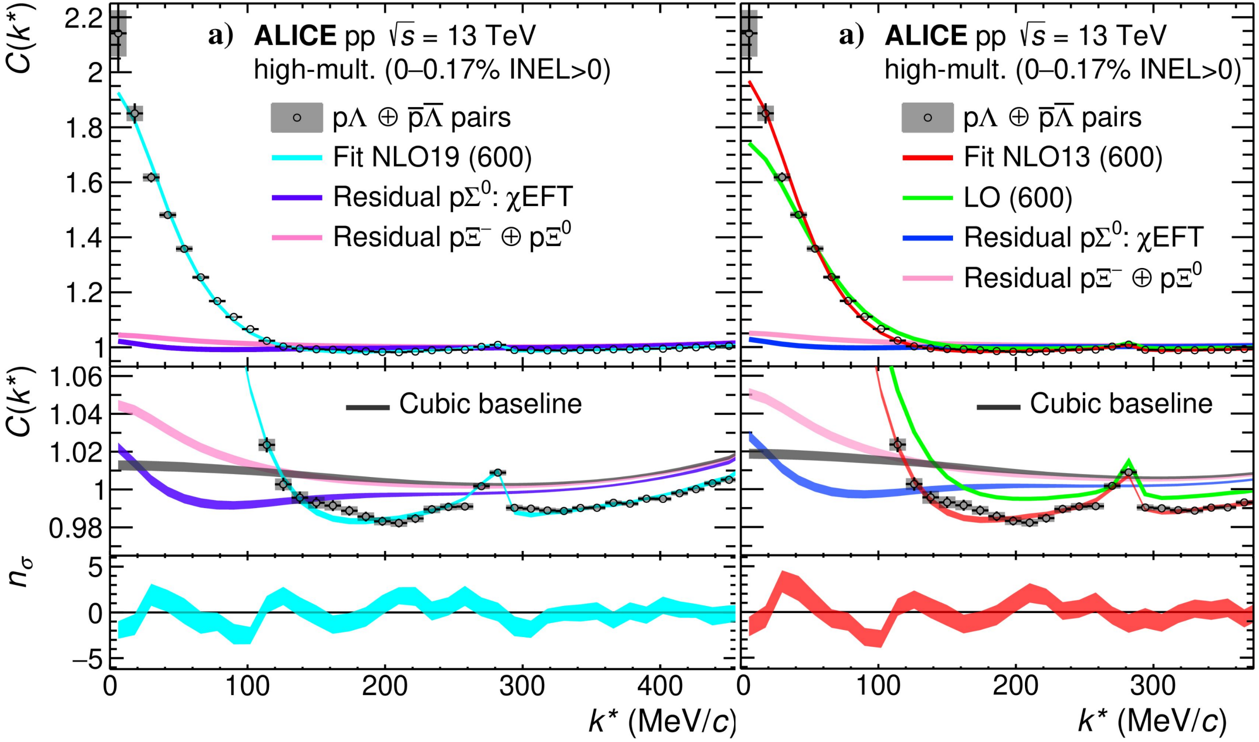


Based on ALICE Coll. *PLB 833 (2022), 137272*

Haidenbauer et al. *Eur.Phys.J.A 56 (2020) 3, 91*

pΛ interaction
Results



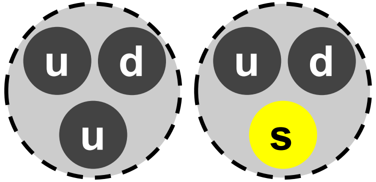


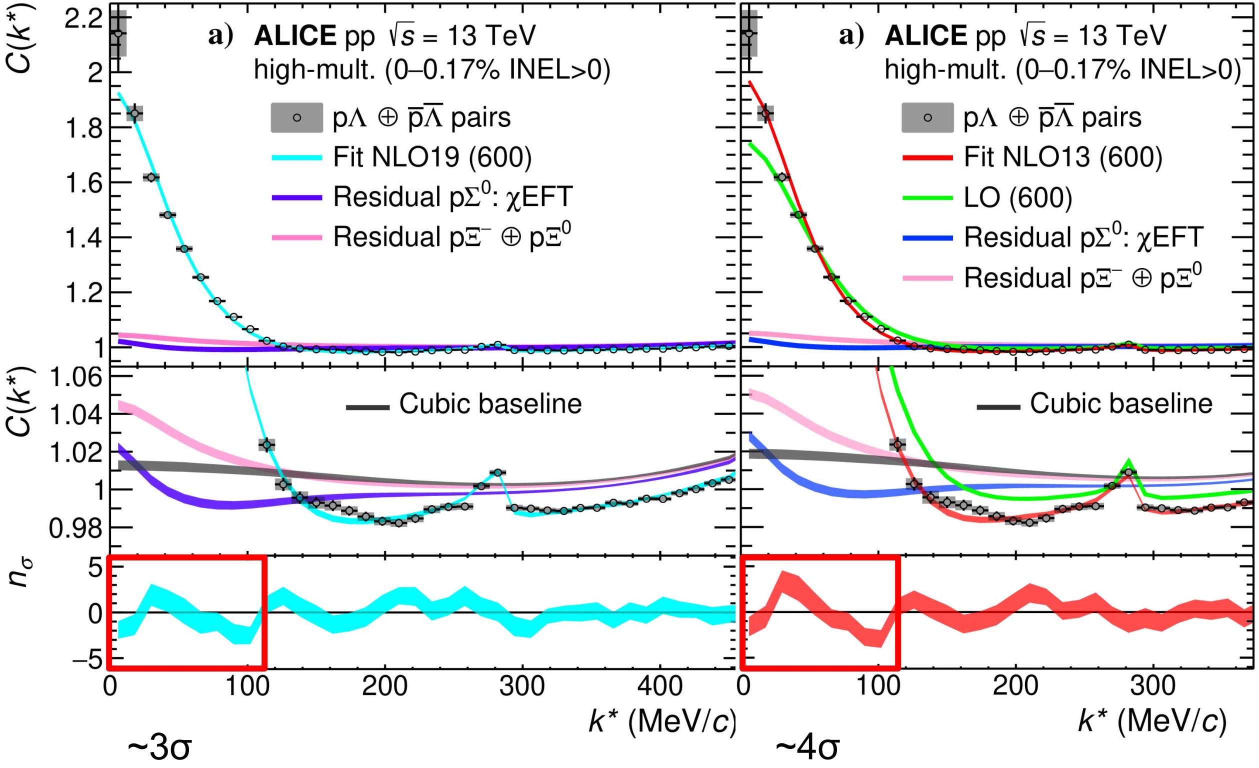
- Observation of the **NΛ↔NΣ cusp.**
- Superior **precision at low momenta** over existing data.

Based on ALICE Coll. *PLB 833 (2022), 137272*

pΛ interaction

Results



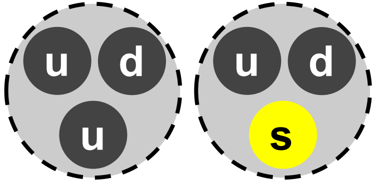


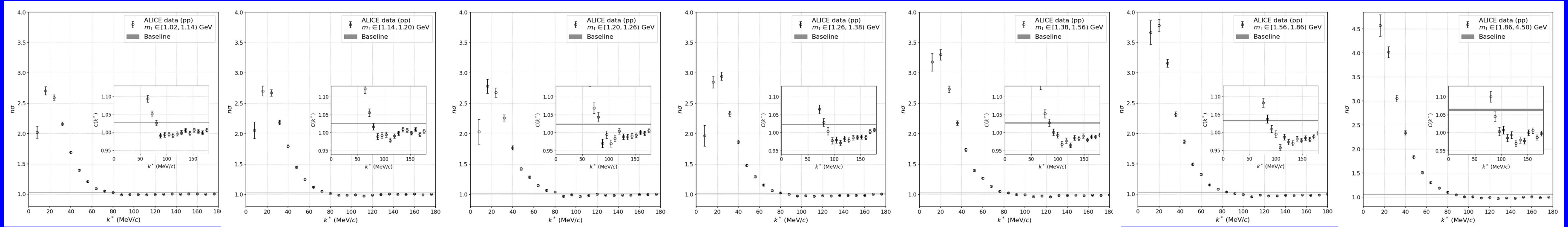
- Observation of the **NΛ↔NΣ cusp.**
- Superior **precision at low momenta** over existing data.
- Preference towards the NLO19.
  Differences in the coupling to NΣ, and in the interplay between two- and three-body forces. Important for the equation of state.
- NLO19 deviates by ~3σ at low k*.
  Further improvement of the model is possible!

Based on ALICE Coll. *PLB 833 (2022), 137272*

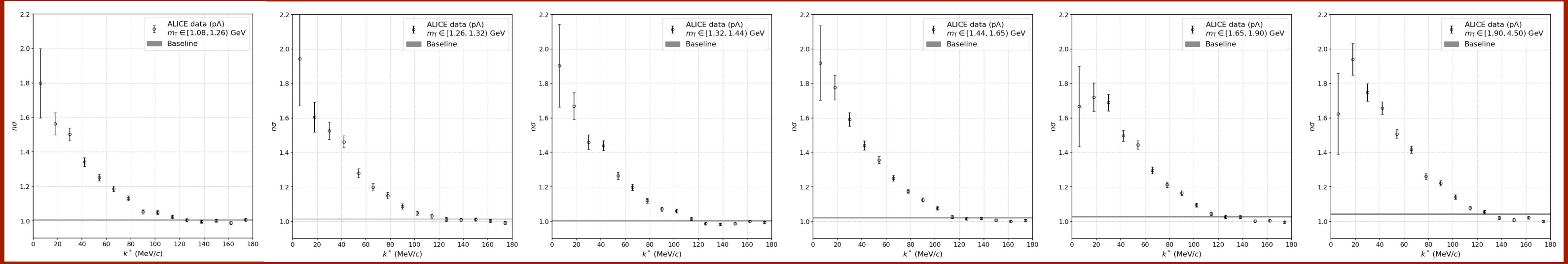
ALICE data

pp and pΛ correlations





mT



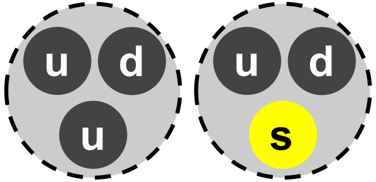
Data: High-multiplicity pp collisions @ 13 TeV from ALICE

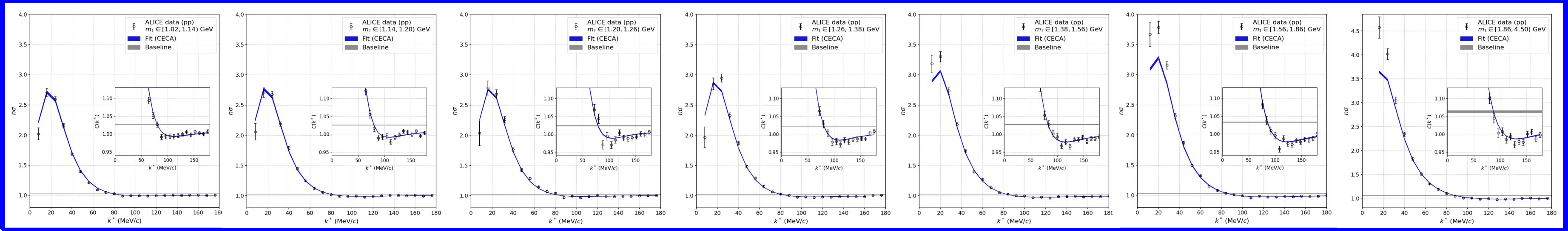
PLB 811 (2020) 135849

PLB 833 (2022) 137272

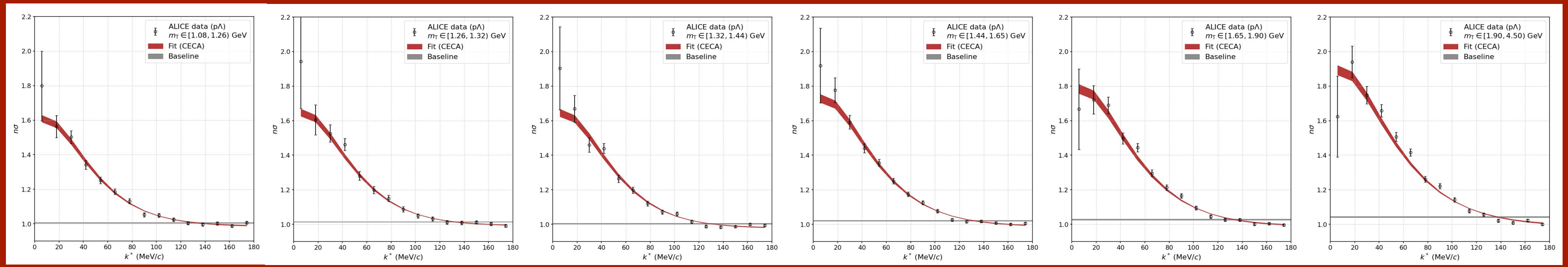
ALICE data + CECA

One source to rule them all





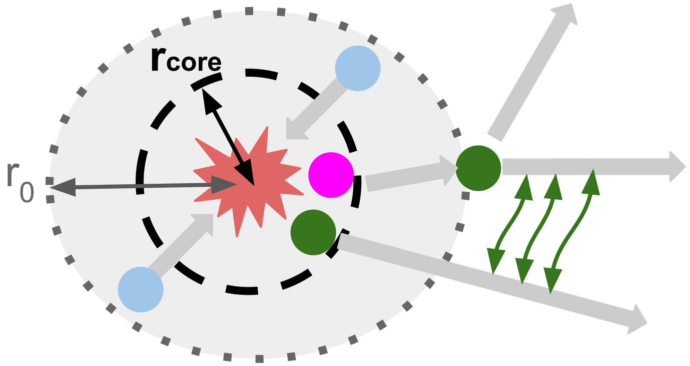
mT

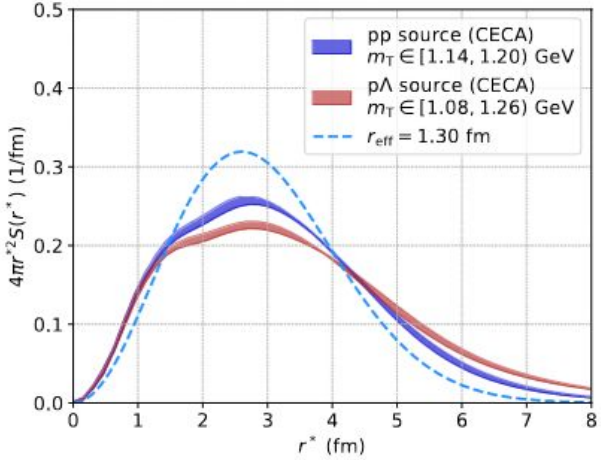


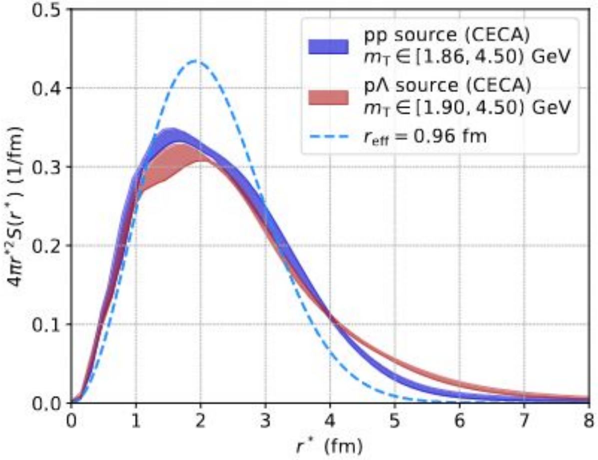
- pp interaction: fixed to the Argonne v18 potential
  Wiringa, Stoks, and Schiavilla, *PRC, 51:38–51, 1995*
- pΛ interaction: Usmani potential, short-range repulsive core fitted
  Usmani et al, PRC, 29:684–687, 1984
- **A combined fit of the mT differential pp and pΛ correlations!**
  Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590

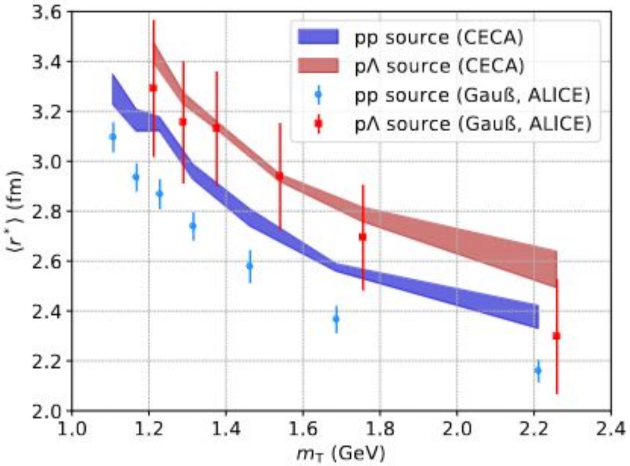
ALICE data + CECA

One source to rule them all



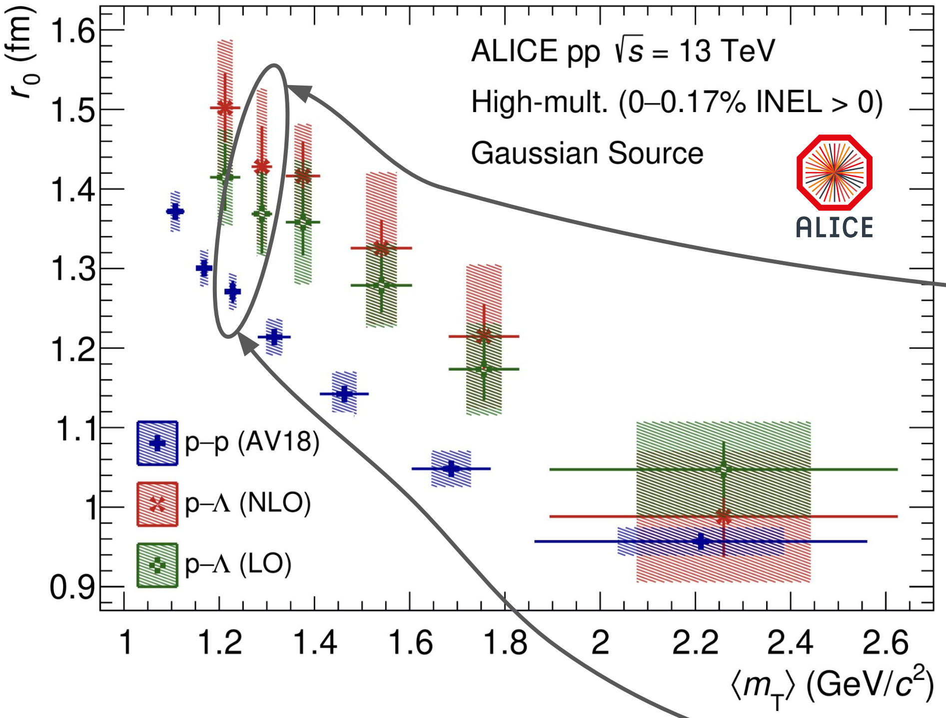




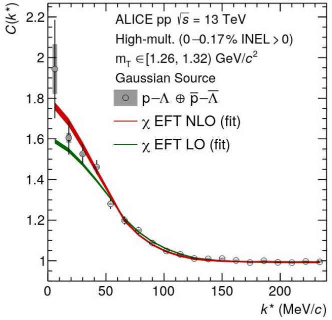


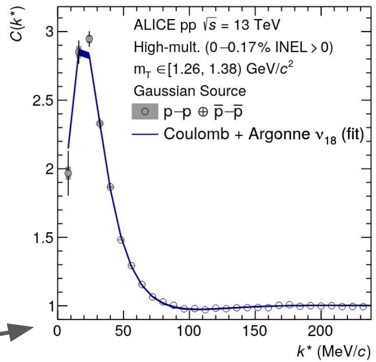
Femtoscopy @ ALICE

In small collision systems (pp)



- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.



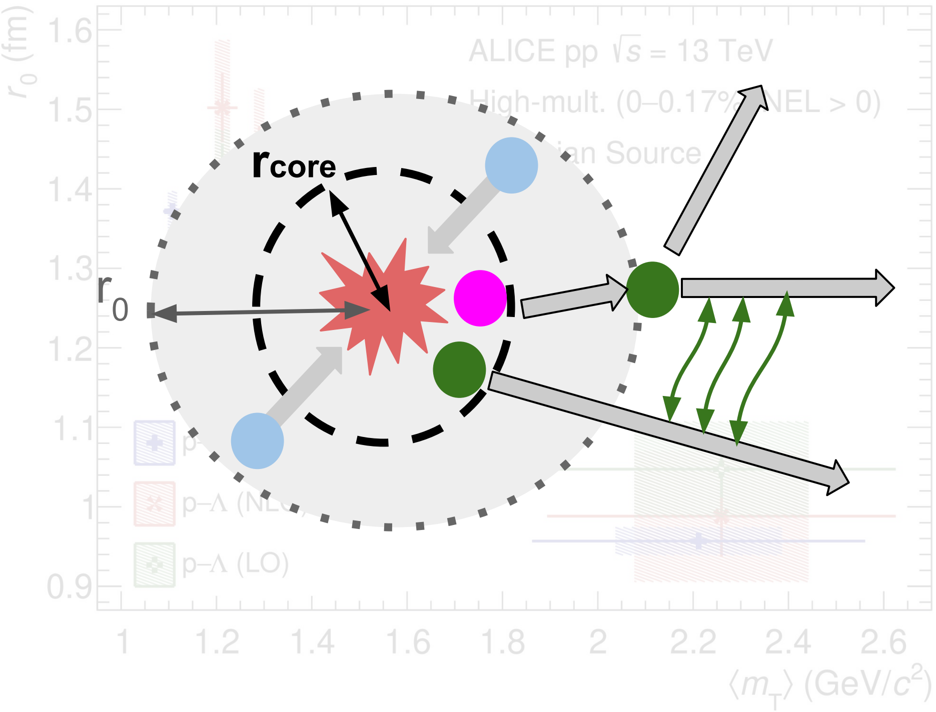


[ALICE Coll. *Phys.Lett.B 811 (2020) 135849*]
[*Corrigendum in 2025*]

Femtoscopy @ ALICE

Resonances source model (RSM)

Details later in the presentation



- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.
- **A hypothesis:**

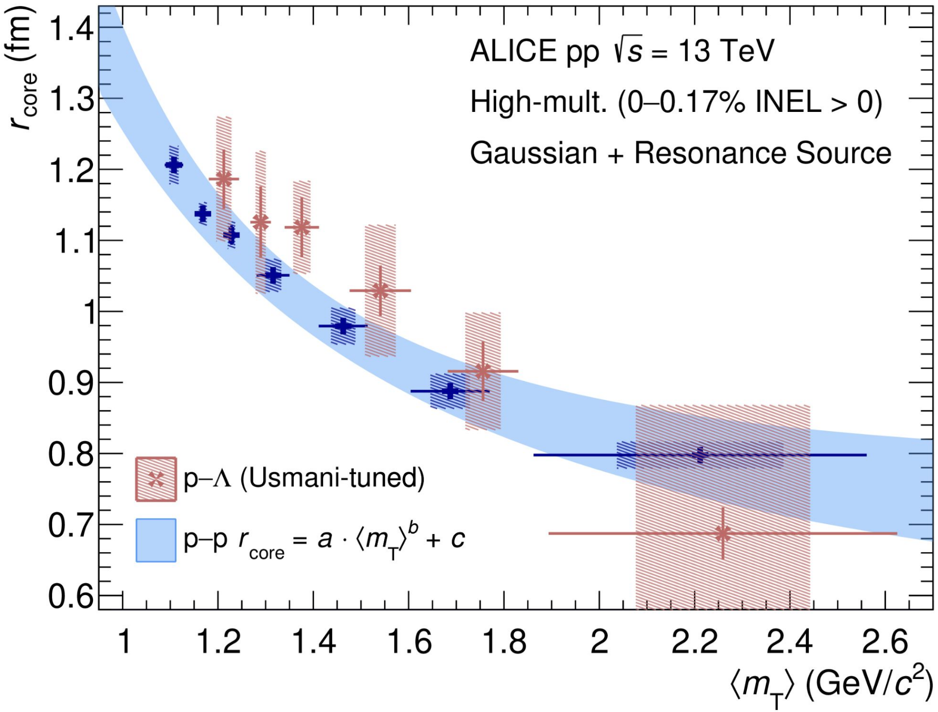
  Gaussian "primordial core" **common for all species** modified by decays of short lived resonances.

  Based on statistical hadronization model ⅔ of all protons and Λs are produced like that. Resonances decaying into Λs, on average, live longer.
  <cτ> for protons c.a. 1.7 fm/c
  <cτ> for Λs c.a. 4.7 fm/c

ALICE Coll. *Phys.Lett.B 811 (2020) 135849*
Corrigendum in 2025

Femtoscopy @ ALICE

Resonances source model (RSM)



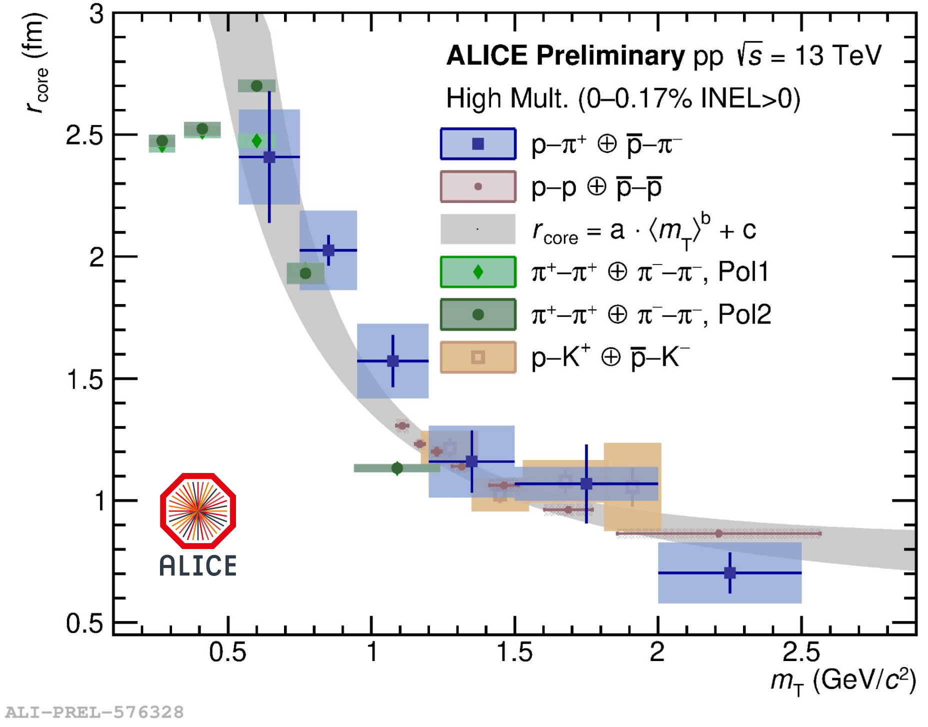
- Study of the pp and pΛ, using a Gaussian source, revealed mT scaling. The source size is different for different species.
- The **breakthrough** of the Resonance Source Model (RSM)
  A "primordial core" **common for all species** modified by decays of short lived resonances.

- Any baryon-baryon pair will follow this scaling, and the source size can be extracted based on the <mT> of the measured pairs!
- This allows for **precision studies of the strong interaction**.

ALICE Coll. *Phys.Lett.B 811 (2020) 135849*
Corrigendum in 2025

Femtoscopy @ ALICE

Resonances source model (RSM)



The scaling (in pp) was everywhere in RUN2

The studies are now commencing in RUN3